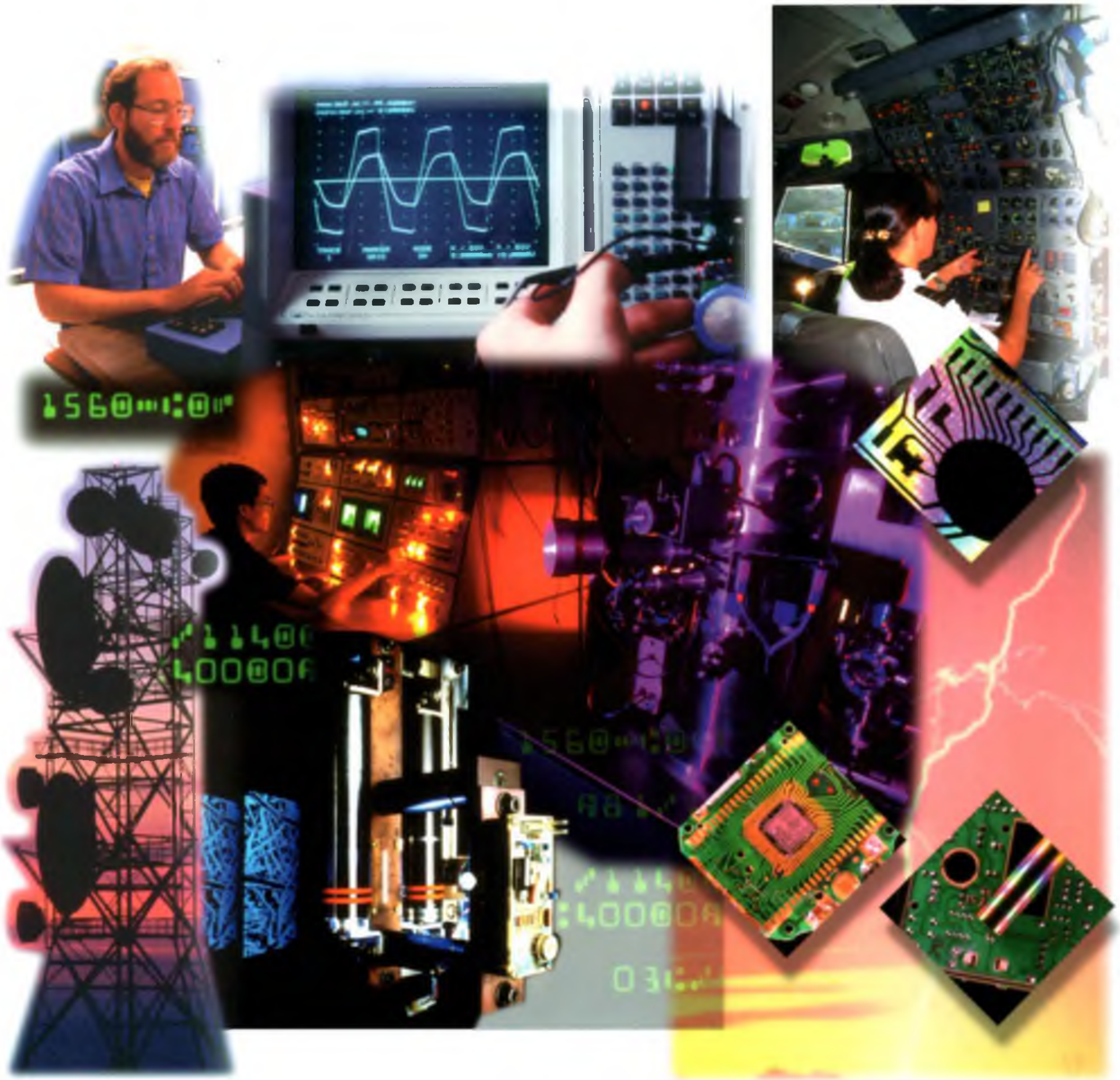
INDIVIDUAL LEARNING SYSTEM



TEXTBOOK

AC ELECTRONICS

Heathkit® EDUCATIONAL SYSTEMS

AC ELECTRONICS

EE-6102-C
595-5800

AC Electronics, Fourth Edition

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Contents

INTRODUCTION

This Heathkit Individual Learning Program, EE-3102-C, is designed to give you a foundation in the principles of "AC Electronics." You will begin with a discussion of alternating current. Then, as you progress through the course, you will be introduced to the characteristics of various components in the AC circuits, as well as applications of the components.

Several experiments are also providcd to give you both the theory and some practical applications. They are designed to reinforce the information that is provided in the text. We urge you to perform the experiments whenever possible.

To perform these experiments, you will need a Heathkit Analog Trainer, such as the ET-3600, and a multimeter. Some of the experiments also require you to use an oscilloscope and one or two probes.

In addition, an audio visual presentation, EEA-3102A, is available for you to use with this course. Although you do not need this package to complete the course, it can give you a different perspective of the text material, as well as additional reinforcement of the concepts in each unit. This package can also serve as an overview, as well as a summary of the "AC Electronics" text.

How do you gauge your learning? Let the objectives be your guide. These carefully constructed objectives are the framework for the course. When you can meet all of the objectives, you have satisfied the requirements of the course. You will find two types of objectives in this course. Broad course objectives are listed following this introduction. More specific unit objectives are listed near the front of each unit. When you can satisfy these unit objectives, you have learned everything that was intended from the units; no matter how easy it seemed.

When you complete the program, you will no doubt want to receive some recognition for your accomplishment. If you complete the final exam and make a passing grade (70% or better), you will receive an attractive Certificate of Achievement and Continuing Education Units (CEU's) that indicate your participation in an adult continuing education course.

The following are general tips for improving the accuracy of your experiments:

1. Be sure that all powered equipment is connected to the same power source.

   This establishes a common reference and helps prevent ground loops.

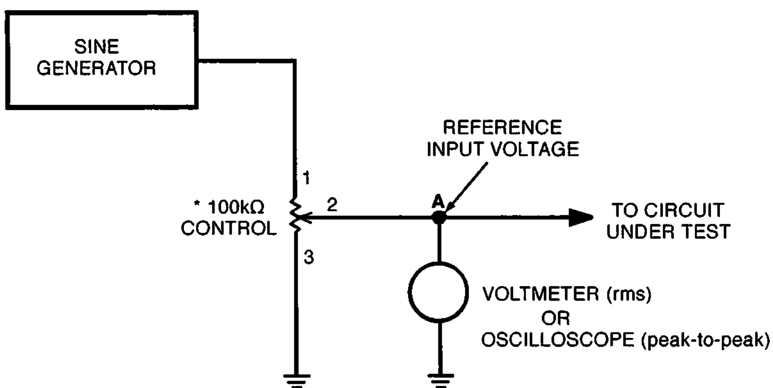
2. Make sure you do NOT inadvertently insert a ground into the circuit under test. Determine if your test equipment reference lead is earth grounded.

   With an ohmmeter set to its R × 1 range, measure the reference lead to the center prong of the power plug. If the reading is zero, your equipment is earth grounded.

   If it is earth grounded, you **MUST** reference all measurements to ground.

3. When you make a comparison between two frequencies, make sure the input reference does NOT change excessively with the change in frequency.

   Tune your source across its frequency range while you monitor the output. If the output amplitude changes or is too high, use the circuit shown below between your signal source and the circuit under test.



*When you use Heathkit Trainers, use the 100 kΩ control that is mounted on the Trainer.

This procedure takes the approximate and relative values out of your calculations and, thus, greatly improve the accuracy of your results and your understanding of the principles being demonstrated.

Remember: The frequency dial represents only a relative value. If you want greater accuracy, monitor the output frequency with a calibrated frequency counter or oscilloscope.

COURSE OBJECTIVES

When you complete this course on AC electronics, you will be able to:

1. State the difference between alternating and direct current.

2. List the advantages that alternating current has over direct current.

3. Describe the operation of a basic AC generator.

4. Determine the effective value, peak value, peak-to-peak value, frequency, and period of an AC sine wave.

5. Explain how to use AC meters to measure current, voltage, and power.

6. Analyze series and parallel AC circuits that contain only resistance, and solve these circuits for voltage, current, and power.

7. Define capacitance, explain the electrical property known as capacitance, and state how capacitors are formed.

8. Define inductance, explain the electrical property called inductance, and explain how inductors are formed.

9. Analyze inductive circuits and determine the resistance, inductive reactance, current, voltage, true power, reactive power, phase angle, and power factor of the circuit.

10. Analyze capacitive circuits and determine the resistance, capacitive reactance, current, voltage, true power, reactive power, phase angle, and power factor of the circuit.

11. Analyze RLC circuits and determine the resistance, inductive reactance, capacitive reactance, true power, reactive power, current, voltage, phase angle, power factor, power factor correction, and resonant frequency.

12. List the characteristics of both series and parallel resonant circuits.

13. Explain basic transformer action.

14. Determine the current, voltage, impedance, and power ratios for a given transformer.

15. Determine the turns ratio necessary for an impedance match.

16. List the electrical properties of a transformer and name five general uses of the transformer.

20. Explain the term remote control.
21. Explain the difference between a generator and a motor.
22. List the basic types of motors.
23. State the type of AC motor most used in industrial applications.
24. Explain the term universal motor.
25. State the advantages and disadvantages of series type motors when compared to shunt type motors.
26. Explain the term compound motor.
27. State the advantage of a servosystem over a synchrosystem.
28. Calculate AC currents for specified appliances.
29. Explain the term service drop.
30. Convert power requirements between horsepower, watts, and current.
31. List 4 safety devices that should be in every home.
32. Explain the difference between reference ground and earth ground.
33. Draw a block diagram complete with current requirements for the electrical loads in your home.

COURSE OUTLINE

UNIT 1 ALTERNATING CURRENT

UNIT 2 AC MEASUREMENTS

UNIT 4 INDUCTIVE CIRCUITS

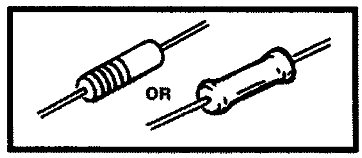
UNIT 6 TRANSFORMERS

PARTS LIST

This list contains all of the parts for the experiments you will perform with this course. The key numbers correspond to the numbers on the illustrations. Some parts are packaged in envelopes. Except for this initial parts check, keep these parts in their envelopes until they are called for in an experiment. A container is provided so you can keep the small parts together in one place.

KEY No.	PART No.	QTY.	DESCRIPTION
RESISTORS (1/2-Watt)			
A1	6-101	1	100 Ω (brown-black-brown)
A1	6-471	1	470 Ω (yellow-violet-brown)
A1	6-102	2	1000 Ω (brown-black-red)
A1	6-472	2	4700 Ω (yellow-violet-red)
A1	6-103	1	10 kΩ (brown-black-orange)
A1	6-473	1	47 kΩ (yellow-violet-orange)
CAPACITORS			
Disc			
A2	21-163	1	1000 pF (may be marked .001 µF or 102K)
Mylar			
A3	27-86	1	.47 µF (may be marked 474K)
A4	27-74	1	.01 µF
A4	27-77	1	.1 µF
A4	27-79	1	.039 µF (may be marked 393K)
A4	27-41	1	.0022 µF (may be marked 222K)
MISCELLANEOUS			
A5	45-610	1	107 mH RF choke
A6	51-97	1	Audio transformer
A7	331-7	1	Solder
A8	344-59	1	Hookup wire (2 ft.)
A9	412-15	1	Neon lamp
A10	490-1	1	Alignment tool
	266-962	1	Small parts container

A1



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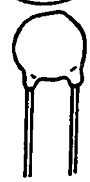

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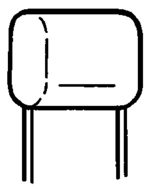

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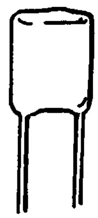

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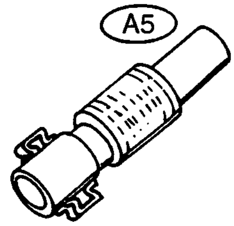

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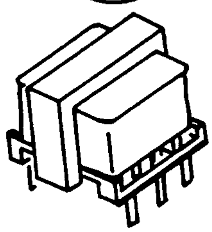

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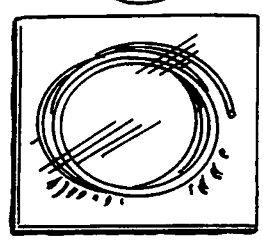

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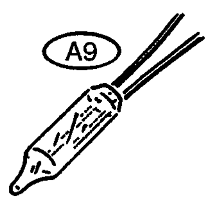

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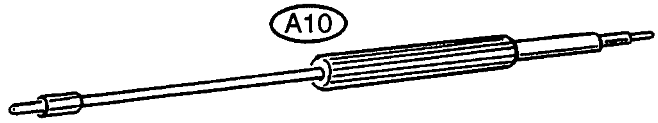


UNIT 1

ALTERNATING CURRENT

CONTENTS

INTRODUCTION

It is essential that anyone who plans to work within the field of electronics have a thorough understanding of the theory and principles of alternating current. Not only does alternating current (commonly called "AC") play an important role in the field of theoretical electronics, but it is also used much more extensively than direct current (DC) in practical applications. In fact, it is virtually impossible to avoid using it or at least being affected by it.

Today, you are surrounded by the miracles of the electronic age. Appliances, tools, and communication equipment simplify everyday living and contribute to a comfortable lifestyle. It is hard to imagine what life would be like without these conveniences.

In this unit, you will begin your study of the principles that have such an impact on your everyday life. You will learn how alternating current is produced and study its electrical characteristics.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define: alternating current (AC), sine wave, cycle, alternation, positive alternation, negative alternation, instantaneous value, peak value, peak-to-peak value, effective value, average value, period, frequency, and hertz.
2. State the difference between alternating current and direct current.
3. Name three advantages of AC current over DC current.
4. Name six general applications of alternating current.
5. Describe the operation of the basic AC generator.
6. State the four factors that affect the voltage or current induced into a conductor.
7. Determine the peak value of a sine wave.
8. Determine the peak-to-peak value of a sine wave.
9. Determine the effective value of a sine wave.
10. Calculate the frequency of an AC signal.
11. Calculate the average value of a sine wave.
12. Determine the period of a sine wave.
13. Name three types of AC waveforms (other than the sine wave).

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "The Importance of AC."	________
☐ Complete Programmed Review Frames 1-14.	________
☐ Read "Generating AC."	________
☐ Complete Programmed Review Frames 15-33.	________
☐ Read "The Sinusoidal Waveform."	________
☐ Complete Programmed Review Frames 34-47.	________
☐ Read "AC Values."	________
☐ Complete Programmed Review Frames 48-62.	________
☐ Read "Nonsinusoidal Waveforms."	________
☐ Complete Programmed Review Frames 63-70.	________
☐ Study the Summary.	________
☐ Complete the Unit Examination.	________
☐ Check the Examination Answers.	________

THE IMPORTANCE OF AC

Because of its characteristics, alternating current is suitable for a variety of commercial, industrial, and military applications. To understand why AC is used, you must understand its advantages and characteristics. This course begins by describing AC, how it is used, and why it is used. This brief discussion about the significance of AC will prepare you for more detailed discussions which follow.

What is AC?

Unlike direct current (DC) which flows only in one direction, alternating current periodically changes its direction of flow. In other words, alternating current flows first in one direction and then in the opposite direction.

Figure 1-1 illustrates the difference between DC and AC. Figure 1-1A shows a resistor that has direct current flowing through it. The current that flows only in one direction is the result of the fixed or constant voltage that is applied to the circuit. This fixed voltage source (referred to as a DC voltage) could be a storage battery or a dry cell. The DC voltage source and the resistor form an elementary DC circuit.

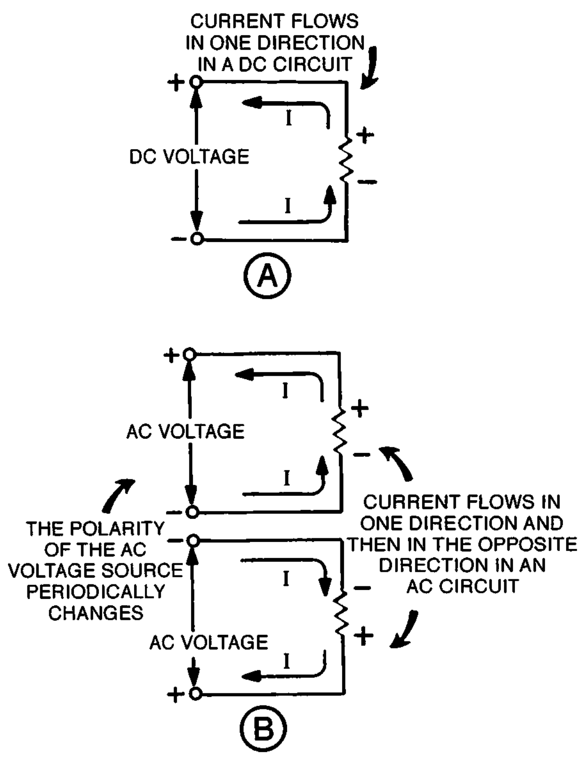


Figure 1-1
Current flow in DC and AC circuits.

Since the voltage source is fixed, the polarity of the source does not change. Therefore, the polarity of the voltage drop across the resistor in the circuit is also unchanged. The current through this circuit flows only in one direction because the DC voltage source remains fixed.

Figure 1-1B shows how alternating current flows through a resistor. In the top figure, current flows in a counterclockwise direction while, in the bottom figure, current flows clockwise. Notice also that the polarity of the source voltage as well as the polarity of the voltage drop across the resistor changes in these illustrations. The change in the polarity of the voltage applied to the circuit results in a change in the direction of current flow and a change in the polarity of the voltage drop. The voltage source shown here is generally referred to as an AC voltage. The resistor and the voltage source form a basic AC circuit.

It is also important to note that a direct current usually has a steady or constant value since it is usually produced by a DC voltage that has a fixed value. However, momentary changes may result if, for example, the DC voltage is adjusted to a higher or lower value or when the circuit resistance changes in value. However, in most DC circuits you are concerned with a steady current which always flows in one direction. By comparison, an alternating current changes in both value and direction. In other words, the current in an AC circuit increases from zero to some maximum value and then drops back to zero as it flows in one direction and then varies in the same manner in the opposite direction. You can control the exact manner in which the current increases and decreases in each direction. This makes it possible to produce various types of AC signals. In fact, a variety of AC voltage sources are used to generate different types of AC voltages that are suitable for a variety of applications. In this unit, you will examine some of the basic types of AC signals that are commonly used.

Why is AC Used?

Alternating current is used widely because of its versatility. Since AC changes in both value and direction, it has characteristics which you can utilize in a wider range of applications than is possible with DC currents.

For example, when a large amount of electrical energy is required for a particular application, it is much easier to generate and transmit alternating current instead of direct current. In applications where large amounts of power are required, devices such as batteries (which produce DC voltages suitable for low power applications) cannot be used. In these applications, electromechanical devices known as generators are used to generate the high voltages and currents required. Although generators can be used to produce both DC and AC electricity, AC generators are less complex, they can be constructed in larger sizes, and are often more economical to operate. Therefore, AC electrical power is simply easier and cheaper to produce.

You can easily change an AC voltage to a higher or lower voltage by passing it through a device known as a *transformer*. Furthermore, this increase (step up) or decrease (step down) in voltage can be achieved with very little loss of power. In other words, the new voltage will provide approximately the same power to a load as you could obtain from the initial voltage. This is an important feature which is used to advantage in many applications. Although it is true that DC voltages may also be stepped up or down, the process is much more complex and costly. Also, considerable power is lost during transformation of DC voltages, which makes the conversion of DC voltages less efficient.

Alternating current may be easily converted into direct current that can, in turn, be used to operate various types of DC circuits or equipment. Although it is true that DC power can also be converted into AC power, the process is much more complex, more expensive, and less efficient. Therefore, when AC is used as the primary source of electrical power, you can still obtain DC when it is needed with a relatively simple conversion process.

The characteristics and features just described may seem to indicate that AC is useful only because it can serve as a source of electrical power to operate electronic equipment. However, this is not the case. Alternating current is also used extensively to transmit information from one location to another. This information carrying ability results because the characteristics of an alternating current or voltage can be made to vary in a desired manner. In other words, the magnitude or amplitude (maximum value in each direction) can be varied to represent intelligence or information. Even the rate at which the alternating current changes direction can be varied to represent intelligence. In this way, information can be inserted within an alternating current or voltage, which makes it possible for the AC to carry information. When alternating currents or voltages are used to carry information, they are often referred to as AC signals. AC signals are widely used in electronics to carry information from one point to another within an electronic circuit. These signals can also be transmitted over long distances with long wires or transmission lines.

Alternating current may also be converted into electromagnetic waves (also called radio waves) which can radiate or travel through space. This action is possible because a conductor which carries alternating current is surrounded by a magnetic field. The field expands and collapses as the intensity and direction of the current changes. If the current changes at a sufficiently high rate of speed, the magnetic field actually radiates outward and the radiated energy varies in accordance with the alternating current. This means that AC signals (which contain information) can be transmitted from one location to another, without wires or transmission lines. You cannot perform this action with direct current.

The points just described illustrate just a few reasons why AC is used. Although there are many additional factors to consider, you can summarize by saying that AC is primarily used to either provide electrical power or to provide a means of transmitting information or intelligence from one point to another.

Where is AC Used?

In any application where large quantities of power are needed, alternating current is generally used. In fact, most electrical energy supplied for domestic and commercial purposes is alternating current.

Large amounts of AC power can be generated at the power plant by extremely large generators which are driven by turbines that are in turn powered by steam or falling water. Power stations that utilize falling water are referred to as hydroelectric stations and are usually located near a dam where the water can be stored and you can control its rate of flow. When steam is used in the generation process, a source of heat is required to produce the steam. This heat may be produced by burning coal, although many of the newer stations use nuclear energy. At one time, windmills were widely used in some of the more remote areas, to generate AC power. Many windmills are still in operation today, but they are not considered suitable for supplying large amounts of power.

The AC electrical power produced by a power plant is distributed as shown in Figure 1-2. The generators at the plant produce a relatively high AC voltage (of ten 3,200 volts or more), and this voltage is passed through power transformers which step it up to an even higher voltage (often as high as 275,000 volts). This extremely high AC voltage is applied to long distance transmission lines, which carry the voltage to the various cities and towns that are serviced by the power plant. At each location where the power is to be used, it passes through power transformers which step it back down to a lower voltage (typically 2,300 volts). The AC voltage is then distributed through wires which are strung on utility poles that are located along roadways, streets and alleys. This relatively high AC volt age may be directly used to power high voltage motors and industrial equipment. The AC voltage must be reduced even further before it can be used in the home. This final step-down is accomplished by a transformer which is usually located on a utility pole. This transformer steps the voltage down to 240 and 120 volts, which is then distributed to the nearby homes.

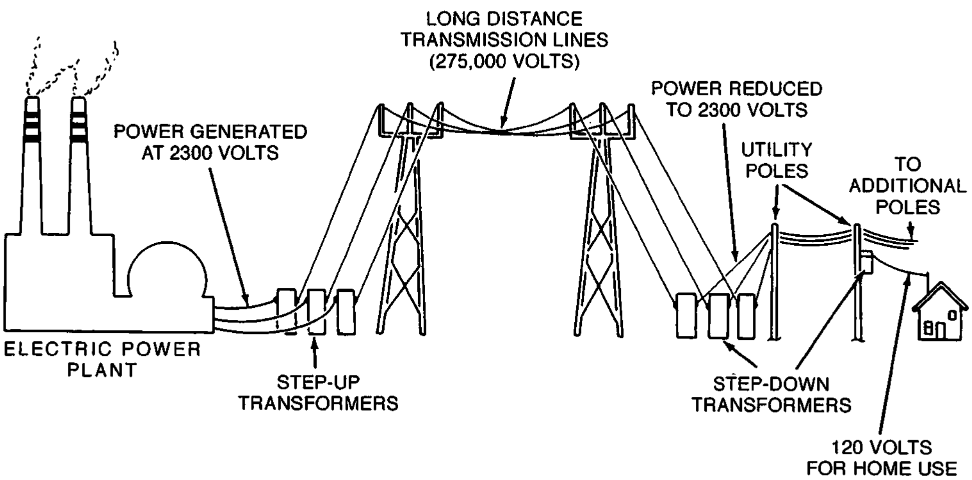


Figure 1-2
A typical electrical power distribution system.

Most of your household wall plugs and light fixtures are 115/120 AC volts at 60 hertz (Hz). Some of the major appliances like stoves, wall heaters, electric furnaces, electric dryers, and some air conditioners use the 220/240 AC voltage source. Wall plugs that are rated at other than 115/120 generally require a special plug. The special plug requirement helps eliminate the possibility of mistakenly plugging an appliance into an improper supply voltage.

In the home, AC power is used for heating, cooking, and illumination. It is used to operate appliances such as clothes dryers, refrigerators, electric ranges, microwave ovens, dishwashers, and vacuum cleaners. In fact, all of the large electrical appliances that are used in your home depend upon the 240- or 120-volt AC power provided by the electric power company.

You should inspect power cords periodically for signs of wear and bare wire. A bare wire can be caused by wearing away a portion of the insulation material that coats the power cord. Keep power cords out of exposed areas. Do not route a power cord or extension cord across a doorway or any place where it might be stepped on or run over by other objects. Most wall receptacles (wall plugs) are rated at 15 amperes. Make sure that you do not demand more current than a receptacle can supply. Besides blowing a fuse, it could start a fire.

If you have an electrical fire, do not pour water on the fire. To put out an electrical fire, use a carbon dioxide fire extinguisher or sand.

Many industries rely on AC power to operate the electric motors that drive their machinery. AC motors are used much more extensively than DC motors because an AC power source in readily available. AC motors are also less expensive, more rugged, more efficient, and require less maintenance than comparable DC motors. In the relatively few applications where DC motors are required, such as the types used to operate elevators and certain machine tools, AC power is converted to DC power which is then used to drive the equipment.

In other industrial applications, AC is used to heat various materials. In these applications, rapidly varying AC currents are allowed to flow through specially shaped coils of wire. The electromagnetic fields produced by the AC currents, cause heat to be generated within any metal object that is placed within its coils. This process is often used to heat-treat metals. A similar process is also used in the medical profession where AC currents are used to produce heat within body tissue.

Without alternating current, radio or television communication would not be possible. This is because AC carries the sound as well as the picture information that is transmitted from one location to another. A typical television broadcasting system is shown in Figure 1-3. The sound and picture information is converted into electrical signals by the microphone and television camera respectively. These signals are applied to the sound and picture transmitters, as shown, where they are used to vary the characteristics of the high power alternating currents which are produced by the transmitters. The resulting high power AC signals contain the sound and picture information and are applied to the transmitting antenna.

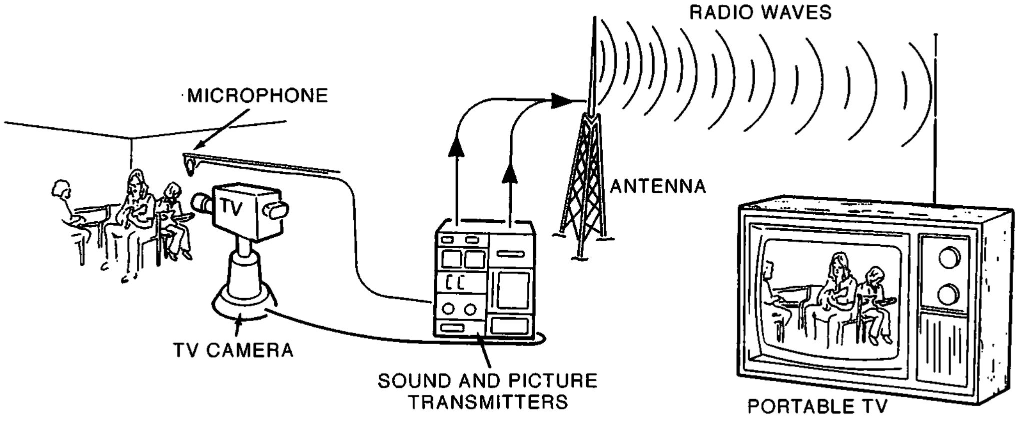


Figure 1-3
A typical television broadcasting system.

The antenna converts the signals into electromagnetic waves and radiates the waves into space. When these waves intercept the antenna on a television set. They produce AC signals within the antenna that are identical to the signals applied to the transmitting antenna. These AC signals are separated and processed by the television set so that the sound and picture information is extracted and converted into an audible and visual display.

AC signals also play an important role in many applications where information must be transmitted from one location to another. For example, generation and transmission of AC signals are utilized in radar equipment, two-way radio communication systems, as well as AM and FM radio broadcast systems. The various telephone systems across the country utilize AC signals, although these signals are carried by wires or transmission lines. Many of the telephone company's transmission lines have been replaced with low-loss fiber optic cables.

In addition, AC signals are used in many short range applications. In a short range application, the distances between the transmitting and receiving points are only a few feet or possibly a few hundred yards apart. Such applications include the radio control systems that are used to control model airplanes, toys, boats, and even cordless telephones. Remote television channel selectors which change the channels on television sets from several yards away, and the electronic garage door opener which allows you to open a garage door without getting out of your car are also types of remote control devices.

As you can see, there are many applications for alternating current. In fact, there are so many that it would be impossible to consider all of them at this time. However, this brief review helps you to understand the important role that AC plays in electronics. AC is used to provide comfort, convenience, and even entertainment for a large number of people.

Programmed Review

All reviews in this text are presented in a programmed instruction format. They will enhance your understanding of the material presented in each section. Read the numbered frames carefully and fill in the missing blanks in each frame. The correct answer appears in parenthesis at the beginning of the next frame. Use a sheet of paper to cover all of the frames below the one you are reading.

1.	Alternating current (AC) periodically changes its direction of flow. In other words, it flows first in one direction and then it flows in the ___________ direction.
2.	(opposite) Alternating currents usually vary in value or magnitude as well as change direction. In other words, an alternating current usually increases from zero to some maximum value and then drops back to zero again in one direction. It then varies in the same manner, but in the opposite ___________.
3.	(direction) In order to produce an alternating current in a circuit, it is necessary to use a voltage source that reverses its polarity as well as its value or magnitude. In other words, an alternating current is produced by an AC ___________.
4.	(voltage) Alternating current is used more extensively than direct current (DC) in applications where large amounts of electrical energy are needed. This is because it is much easier and cheaper to generate a large amount of AC power than it is to generate a large amount of _________ power.
5.	(DC) An AC voltage can be easily stepped up to a higher voltage or reduced to a lower voltage without a significant loss in power. This means that the new voltage can provide almost the same amount of ___________ to a load as could be obtained from the initial voltage.
6.	(power) Although AC power may be the only type of electrical energy available, it is still possible to obtain DC power you need it. This is because it is relatively easy to convert _________ to _________.

7.	(AC to DC) Alternating current may also be used to carry information or intelligence by varying its characteristics in a desired manner. When it is used in this manner, the resulting alternating current is referred to as an _________ signal.
8.	(AC) Alternating currents may also be transmitted over long distances through wires or transmission lines or by converting them to radio waves which can travel through ____________ .
9.	(space) The electrical power that is generated by many power stations across the country and distributed to various businesses and homes is actually AC power. This power is generated at a relatively high voltage, but it is stepped up to an even higher ____________ for transmission over long-distance transmission lines.
10.	(voltage) At the point where the AC power is to be utilized, it is ___________ ___________ to a lower voltage which is safe to use.
11.	(stepped down) Commercial AM and FM radio stations, as well as various local television studios, broadcast sound and picture information via AC signals. These signals are transmitted to various radio and television sets inside homes across the country. Such AC signals are transmitted in the form of _____________ waves.
12.	(electromagnetic or radio) Telephone companies also uses AC signals, but these signals are sent from one location to the next through _______________ lines.
13.	(transmission) AC that is used by the electrical power companies and many AM, FM, and TV broadcast systems across the country illustrate two fundamental applications of alternating current. These two basic applications show that AC is useful both as a source of electrical ___________ and as a means of carrying _____________ .
14.	(power, information)

GENERATING AC

Although alternating current may be generated in a number of ways, the most basic means of obtaining AC is with an electromechanical device known as an *AC generator* or *alternator*. An AC generator produces an alternating voltage which in turn develops an alternating current through any load (resistor, lamps, etc.) that is connected to the generator's output terminals. Basically an AC generator produces an AC voltage by turning a loop of wire within a magnetic field. The relative motion between the wire and the magnetic field causes a voltage to be induced into the wire. This voltage changes in magnitude and polarity as the speed and direction of the wire changes in relation to the magnetic field.

The next few paragraphs describe the conditions that are necessary to produce a voltage within a conductor. You will see how a simple AC generator is capable of producing an alternating voltage.

Electromagnetic Induction

An AC generator produces an alternating voltage because it uses a fundamental, but important, process known as electromagnetic induction. Electromagnetic induction is the process of inducing a voltage within a wire or conductor by moving it through a magnetic field.

In Figure 1-4, notice that a short wire or conductor has been inserted into the magnetic field that exists between the north (N) and south (S) poles of two magnets. When you move the conductor upward through the magnetic field, it cuts across the magnetic lines of force (also called flux lines) that are produced by the magnets. As the magnetic flux lines pass through the conductor, the free electrons in the conductor are forced to move. These free electrons move towards one end of the conductor, which leaves a deficiency of electrons at the other end. This excess and deficiency of electrons causes the opposite ends of the conductor to take on negative (–) and positive (+) charges as shown. In other words, a difference of potential or voltage is developed across the conductor.

The voltage that is developed across the conductor shown in Figure 1-4 results due to the relative motion between the conductor and the magnetic lines of force. This relative motion must exist in order for a voltage to be produced. The conductor may move while the field remains stationary, or you could hold the conductor stationary while you move the field. Either condition produces a voltage. If there is no relative motion, no voltage is produced.

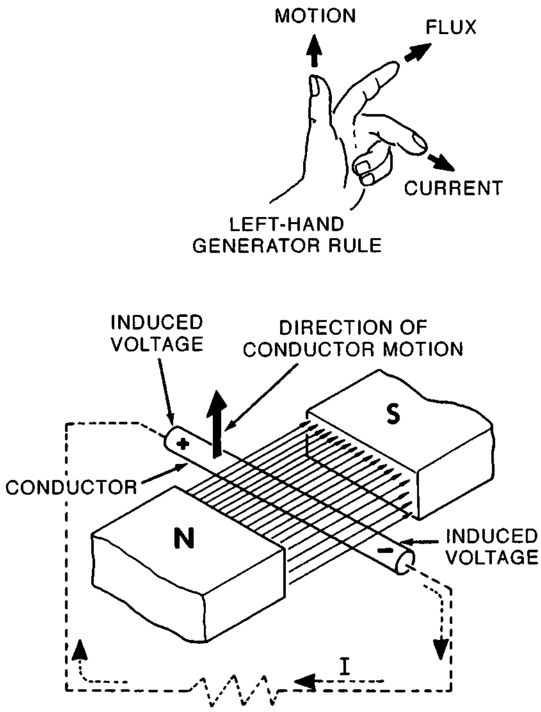


Figure 1-4
A voltage is induced in a conductor
which moves through a magnetic field.

The voltage produced within the conductor is generally referred to as an *induced* voltage. This voltage is induced within the conductor regardless of whether there is current flowing through the conductor or not. In fact, a continuous current cannot flow through the conductor unless there is a **complete** circuit. You might form such a circuit by connecting a load (such as a resistor) across the conductor as shown by the dashed lines in Figure 1-4. Current could then flow through the load resistance as shown.

The direction that the conductor is moving and the direction of the magnetic field determine the polarity of the voltage induced within the moving conductor. Note the direction of conductor motion and the direction (north to south) of the magnetic flux shown in Figure 1-4. Note the polarity of the induced voltage and the direction that current travels when a complete current path is provided. If you reverse either the direction of conductor motion or the direction of the magnetic flux, the polarity of the induced voltage is reversed, and current flows in the opposite direction.

You can use the left-hand generator rule, illustrated in Figure 1-4, to determine the direction of current flow or the polarity of induced voltage within a conductor. When you position your left hand as shown, your thumb indicates the direction of conductor motion, your index finger points in the direction of magnetic flux, and your middle finger, which is bent out from the palm at a 90 degree angle, points in the direction of the induced current.

The amount of voltage that is induced in a conductor is determined by several factors. First the induced voltage is affected by the strength of the magnetic field. A stronger magnetic field results in more lines of force per unit area. This means that there are more lines to cut and the induced voltage increases. When you reduce the field strength, fewer lines of force exist, and the induced voltage decreases.

Induced voltage also depends upon the speed the conductor moves. The faster the conductor moves, the greater the induced voltage. This occurs because the faster moving conductor cuts more lines of force in a given period of time. When you reduce the speed of the conductor, fewer lines of force are cut per unit of time and the induced voltage decreases.

The length of the conductor within the magnetic field also affects the induced voltage. The longer the conductor, the greater the induced voltage. The longer conductor cuts more lines of force as it moves through the magnetic field. A shorter conductor intercepts (cuts) fewer lines of force, and induced voltage is decreased.

The angle at which the conductor cuts the magnetic field also affects the induced voltage. When a conductor moves at a right angle (90 degrees) with respect to the magnetic field, as shown in Figure 1-4, maximum voltage is induced. When the angle between the field and the direction of conductor motion decreases, induced voltage decreases. This relationship is true regardless of the direction of the induced voltage.

The relationship between the direction of the field and the direction of conductor motion is shown in Figure 1-5. If the conductor (viewed edgewise) moves straight up from the starting position (direction A), it moves at a right angle (90 degrees) with respect to the field. At this time, the conductor cuts the maximum number of lines per unit of time and the induced voltage is maximum. The voltage induced

into the conductor causes current to flow out of the page or toward you (according to the left-hand rule). The same condition exists when the conductor moves in the opposite direction (direction E). In this case, the conductor is still moving at a right angle with respect to the field. The change in direction still induces a maximum current, which develops a maximum voltage. The only difference caused by reversing the direction of conductor motion is that the induced current flows into the page. In other words, the direction of current flow reverses.

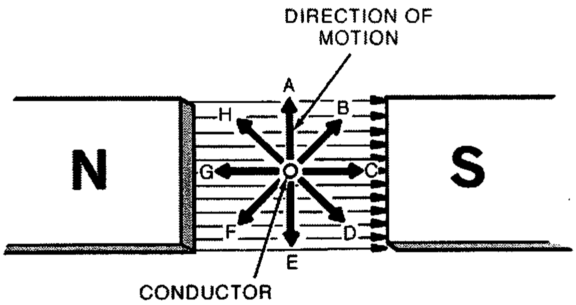


Figure 1-5
The induced voltage is determined by the rate at which the lines of force are cut.

If the conductor moves in direction B at the same speed, the cutting angle decreases below 90 degrees. This means that the conductor must travel further between lines of force. This results in fewer lines being cut for the same distance of travel. The induced voltage is less than it is at points A or E. This is also true when the conductor moves in direction H.

In either direction, B or H, the cutting angle is the same and the induced voltage is the same. In each case, the induced current flows out of the page. The cutting angle is the same when the conductor moves in the direction of D or F. The amount of induced voltage is the same in both examples. However, in direction D or F the induced current flows into the page.

If the conductor moves in either direction C or G, the cutting angle is effectively zero. At this time, the conductor is parallel with the lines of force and no lines are cut. Under these conditions, no voltage is induced in the conductor and no current flows.

Remember, the amount of voltage induced into a conductor is affected by the following four factors:

1. The strength of the magnetic field.

2. The speed the conductor moves.

3. The length of the conductor in the field.

4. The angle at which the conductor cuts the field.

Although these four factors effectively state the conditions which affect the voltage induced into a conductor, it is possible to formulate one simple rule which takes all of these factors into account. This simple rule is:

The voltage induced into a conductor is directly proportional to the rate at which the conductor cuts the magnetic lines of force.

The word rate in this rule indicates the number of lines of force that are cut per second. The rule indicates that the induced voltage is proportional to the number of lines of force that are cut per second. When more lines of force are cut per second, the induced voltage increases. When fewer lines are cut per second, the voltage decreases. You can increase the number of lines of force that are cut per second (the rate) by increasing the strength of the field, the speed of conductor motion, the length of the conductor, or the cutting angle.

A Simple AC Generator

You can form a simple AC generator by bending a wire or conductor into the shape of a loop, and then mounting the loop so that it can rotate within a magnetic field. When the wire loop rotates, an AC voltage is induced into the loop. The only other considerations are to provide a convenient means of extracting the AC voltage generated within the rotating loop and applying this voltage to the load.

GENERATOR CONSTRUCTION

An AC generator is shown in Figure 1-6. It consists of a wire loop called an *armature*, which is mounted so that it rotates within a magnetic field. The magnetic field exists between the north and south poles of a magnet. The magnet that is used for this purpose is commonly referred to as a *field magnet.* The field magnet is constructed so that it produces a strong, concentrated magnetic field between its poles. It can be either a permanent magnet or an electromagnet. The electromagnet is preferred in applications where a high field strength is required to produce substantial output power.

The AC voltage that is induced into the rotating armature must be extracted at the ends of the wire loops which form the armature. However, the armature constantly turns, which makes it impossible to permanently attach any wires or leads directly to the armature. For this reason, it is necessary to use some type of sliding contact at each end of the wire loop. As you can see in Figure 1-6, two cylindrical metal rings are attached to the opposite ends of the loop. These metal rings are called *slip rings*. An external circuit, or load, is connected to these slip rings through contacts which are held against the rings. These contacts are made from a soft but highly conductive material (usually carbon), and are called *brushes*. The brushes slide against the slip rings as the armature turns. The brushes serve as two stationary contacts to which an external load can be connected. The brushes are the output terminals of the generator. Simply stated, the AC output voltage is applied from the armature, through the brushes, to the load.

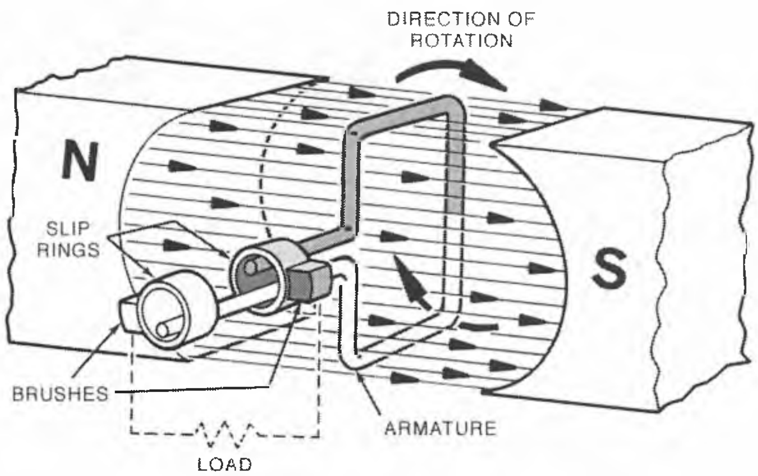


Figure 1-6
A basic AC generator.

GENERATOR OPERATION

In order to function properly, an AC generator must operate so that its armature rotates at a constant speed. As the armature rotates in the magnetic field, one side moves down through the magnetic field while the other side moves up. Note that during each complete revolution of the armature, each side must move down and then up through the field. Furthermore, each side of the armature always remains in contact with its respective brush through a slip ring. Keep these considerations in mind, while you examine the basic action that takes place during one complete revolution of the armature in the following paragraphs.

Figure 1-7 shows an armature is shown in four specific positions. These are intermediate positions which occur during one complete revolution of the armature. Note that one side of the armature and its associated slip ring and brush are black, while the other side is white. These two colors help you keep track of each side of the armature. Also, a resistive load is connected to the brushes so that a complete circuit is formed. The complete circuit allows current to flow through the armature to the load, and a voltmeter monitors the output voltage. Note that the voltmeter is connected across the load.

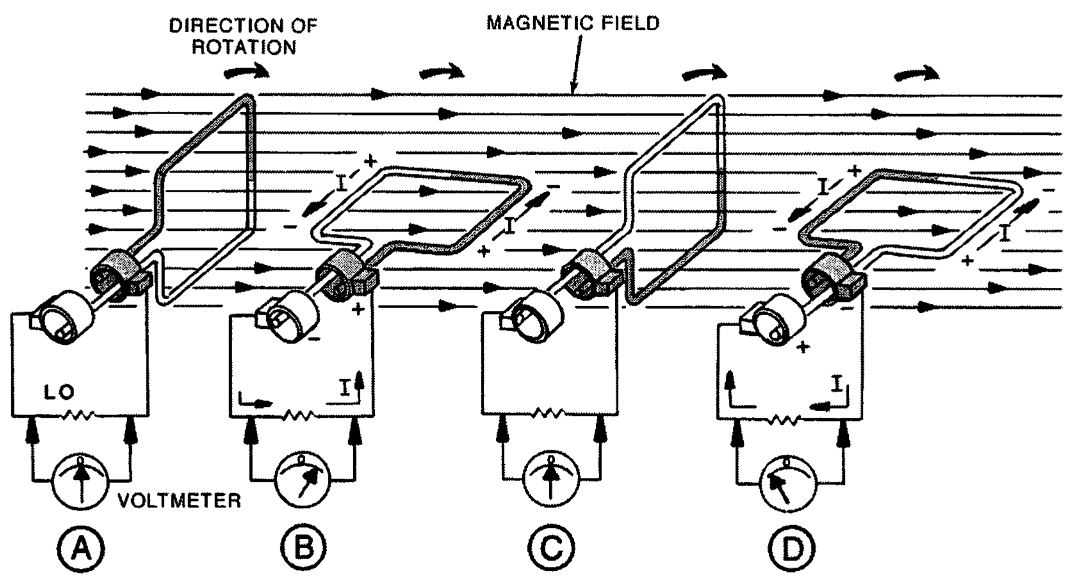


Figure 1-7
Generating an AC voltage.

Assume that the armature begins to rotate in a clockwise direction from the initial position shown in Figure 1-7A. Note that initially the black side of the armature is on top and the white side is on the bottom. As the armature moves from this starting position, the black side moves from left to right, and the white side moves from right to left. However, both sides move parallel to the lines of force (no lines are cut). When a conductor moves parallel to the field, the induced voltage is zero. Note that the voltmeter, which is connected to the brushes, indicates zero at this time.

As the armature rotates from the position shown in Figure 1-7A to the position shown in Figure 1-7B, the black side moves down through the field while the white side moves up. The opposite side of the armature therefore cuts the magnetic lines of force in opposite directions. The polarity of the voltage induced in the black side is opposite the polarity of the voltage induced into the white side. However, the voltages induced in each side are series-aiding and the two sides of the armature form a complete loop. These induced voltages are equal in value. Therefore, the voltage which appears at the brushes, is equal to the sum of the voltages induced into each side.

The polarity of these voltages are shown in Figure 1-7B, along with the resulting currents. Note that series-aiding voltages produce a current that circulates through the armature and the load.

As you examine Figure 1 -7B, note that the armature is horizontal. In other words, the black and white sides of the armature cut the magnetic lines of force at right angles (the fastest cutting rate), which results in the maximum induced voltage. At this time, the output voltage that is applied to the load is at its maximum value as indicated by the voltmeter. It is important to note that the output voltage does not suddenly jump from zero to maximum. The output voltage increases at a specific rate. As the armature rotates from the position shown in Figure I -7A to the position shown in Figure 1-7B, it cuts the magnetic lines of force at an ever increasing angle until maximum voltage is obtained. This causes the output voltage to increase smoothly from zero to its maximum value.

When the armature rotates from the position shown in Figure 1-7B to the position shown in Figure 1-7C, it cuts the magnetic lines of force at a slower and slower rate. When the armature reaches the position shown in Figure 1-7C, the opposite sides of the armature are parallel to the lines of force and no flux lines are cut. This means that the output voltage decreases from maximum to zero as the armature moves to the position shown in Figure 1-7C. The corresponding load current also decreases to zero as the output voltage decreases.

At this point, the armature has completed one-half of a revolution and produced an output voltage that has increased from zero to a maximum value and back to zero. The corresponding load current also varied in the same manner. It is important to note that up to this point the output voltage changed only in value and not in polarity. This is defined as an *alternation*. To be more specific, from zero to maximum and back to zero is described as the positive alternation of an AC waveform. Later, this is described as one-half of a sine wave.

As the armature continues its rotation from the position shown in Figure 1-7C, to the position shown in Figure 1-7D, the opposite sides of the armature move across the magnetic lines of force, in opposite directions. However, the black side of the armature now moves up and the white side moves down. This is exactly opposite to the situation which occurred during the first one-half revolution. Therefore, the voltages that are induced into each side of the armature, have polarities which are opposite to those induced earlier. These induced voltages series-aid, as before, to produce an output voltage.

The output voltage now has a polarity that is exactly opposite to the polarity that was produced earlier. As the armature moves to the position shown in Figure 1-7D, the new output voltage (of opposite polarity) increases to maximum because the armature cuts the lines of force at the fastest rate in this position. This maximum voltage is indicated on the voltmeter which is connected across the load. The load current is also maximum at this time and flows in the direction shown. The amplitude or value is exactly the same as before, but the polarity of the voltage is opposite its initial direction.

The armature completes a full revolution by returning to its initial position as shown in Figure 1-7A. As the armature continues rotating toward its initial position, the armature cuts the lines of force at a decreasing rate, until no lines are cut. This causes the induced voltage within the armature and the resultant output voltage to decrease to zero. The corresponding load current is also zero at this time.

As you can see, one complete revolution of the armature produces a voltage (and corresponding load current) that changes in both magnitude and direction. Therefore, the output voltage and current are AC values. This discussion is not a full description of exactly how these AC quantities vary. You only learned what an AC output is and that an AC output voltage is produced by generator action.

Look again at the generator action that was just described and consider exactly how an AC output voltage is generated. You will again rotate the armature one complete revolution (360 degrees) through the magnetic field. This time, instead of examining only the maximum and minimum points, you will consider the action that takes place at a number of intermediate armature positions.

Since the voltage induced in each side of the armature is series-aiding, it is necessary to observe only the voltage that is induced in one side of the armature. The one-half armature loop rotates through 16 different positions as depicted in Figure 1-8. The conductor rotates through the magnetic field in a clockwise direction.

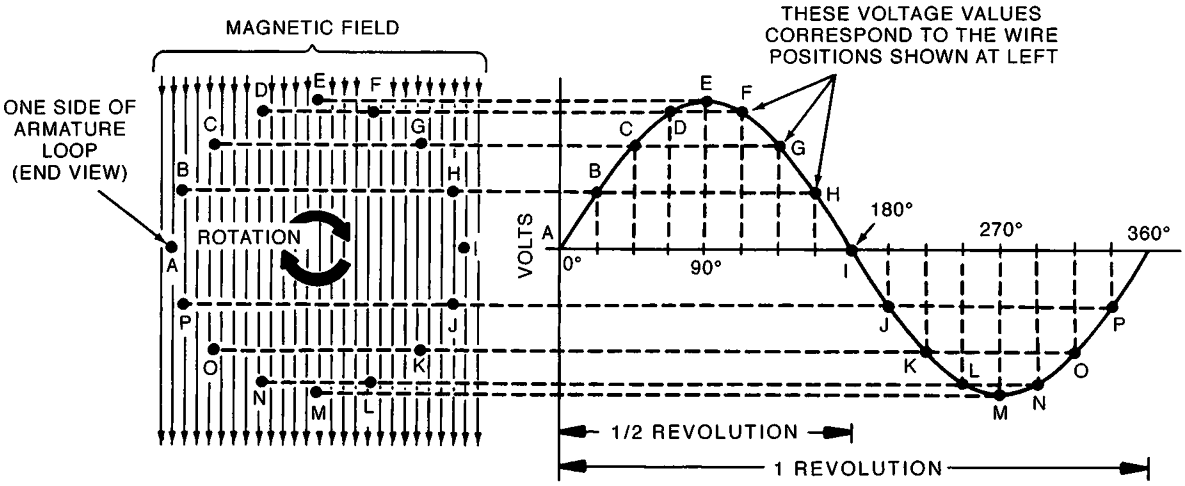


Figure 1-8
Plotting the AC output voltage.

At position A, the wire moves parallel with the lines of force and no voltage is induced. However, as it moves through positions B, C, D, to E, it cuts lines of force at a faster and faster rate. At position E, the wire moves at a right angle (90 degrees) with respect to the field. The voltage induced into the wire is proportional to the rate at which the lines of force are cut. Since the cutting rate increases in a nonlinear manner, the voltage increases in the same way.

This increasing nonlinear voltage is shown graphically in Figure 1-8. The voltage graph was made by marking off the angular rotation of the wire (in degrees) along a horizontal line. This horizontal line is calibrated for one complete revolution of the wire (360 degrees). The value or amplitude of the voltage that is induced within the wire is plotted vertically as shown. Note that five voltage values have been plotted that correspond to wire positions A through E. Each successive value is higher and corresponds to the rate at which the magnetic lines of force are cut. These values are then connected to form a continuous line. The resulting curve shows how the induced voltage varies when the armature rotates one quarter of a revolution, or 90 degrees. Note that the voltage value increases rapidly from zero (at zero-degree rotation) and tapers off to a maximum value (at 90 degrees of rotation).

As the wire continues its rotation past position E and moves through positions F, G, H, and 1, it cuts lines of force at a slower and slower rate. This causes the value of the induced voltage to decrease from a maximum value (at 90 degrees) to a minimum value (at 180 degrees). At position 1, the wire is moving parallel to the magnetic flux lines. At this time, no lines are cut and the induced voltage is again

The induced voltage values which correspond to wire positions F through I are plotted on the voltage graph as shown. Notice that these values (F through 1) are successively lower, with the value at I equal to zero. When you join these voltage values with a continuous line, you can see that the voltage decreases slowly from its maximum value, at a faster and faster rate, until it reaches zero. The voltage curve, between values E and 1, shows how the voltage varies when the armature rotates an additional 90 degrees, which is the second quarter of one revolution.

At this point, the armature has rotated one half of one revolution (180 degrees) and has produced a voltage that varies from zero to a maximum value and back to zero. When the armature moves past position 1, it starts cutting flux lines. This time the armature loop moves in the opposite direction through the magnetic field. Therefore, the polarity of the voltage that is induced into the armature during this alternation is opposite to the polarity of the voltage that was produced during the first one-half revolution (positive alternation).

As the armature moves from position I through positions J, K, L, and M, it cuts the lines of force at an increasing rate. The amplitude of the induced voltage is the same as it was when the armature moved from position A to position E. The only difference is that the induced voltage now has the opposite polarity. To prove that the polarity is opposite, you can plot the voltage values which occur at positions J, K, L, and M below the horizontal line as shown. This portion of the curve shows that the voltage varies from zero to a maximum value in the opposite direction as the armature wire rotates from the 180 degree position to the 270 degree (position M).

When the armature moves to positions N, O, and P, it cuts the lines of force at a decreasing rate. When it reaches position A (its initial starting position), it has completed one complete revolution (360 degrees). At this point, the armature again moves parallel to the lines of force and no flux lines are cut. The voltage drops from its maximum value back to zero, as shown. The voltage produced during the second half of rotation (between 180 degrees and 360 degrees), increases from zero to a maximum negative value and back to zero.

One complete revolution of the armature produces an AC voltage that varies in both amplitude and direction as shown in Figure 1-8. During one-half of the revolution (the positive alternation), the voltage increases from zero to maximum and back to zero. During the next half of a revolution (the negative alternation), the voltage increases from zero to a negative maximum and back to zero again.

When this AC voltage is applied to a load, the resulting current through the load varies in the same manner. In other words, the current will increase and decrease in one direction and then increase and decrease in the opposite direction.

One complete revolution (360 degrees) is made up of a positive (0 to 180 degrees) and a negative (180 to 360 degrees) alternation. These two alternations comprise what is called a cycle of AC. A cycle of AC is the combined time that it takes to generate the positive and negative alternations. This is also defined as the period of an AC waveform.

Since the armature of an AC generator rotates at a constant speed, the AC output voltage produced by the device continually changes in value and direction, as shown in Figure 1-8. Each complete revolution of the armature causes the output voltage to vary in the manner shown.

The AC generator just described is the simplest device that can be used to generate AC voltages. The AC generators used to produce electrical power for commercial applications are more complex in construction. However, all AC generators operate with the principles just described. Practical AC generators utilize many loops of wire, within their armatures, to increase the induced voltage to a much higher value. These generators may also contain more than one pair of north-south magnetic poles. When more than one pair of poles are used, one revolution of the armature can produce more than one AC voltage variation.

Some AC generators that are designed for low power applications can be very small. For example alternators that are used on most automobiles, are small AC generators that are only six or seven inches in diameter. These small AC generators can produce a few hundred watts of output power. These alternators (generators) are powered by the car's engine and used to produce an AC voltage that is converted to a DC voltage. The DC voltage is then used to operate the car's electrical system. The newer alternators are used in place of DC generators (which were once widely used) because they are more efficient and require less maintenance. The process of converting AC to DC is relatively easy and inexpensive. The process of converting AC to DC is called rectification and will be explained in detail later in this course.

Some AC generators are designed to produce large amounts of electrical power and are extremely large. For example, an AC generator that is used by an electric power company might be too large to fit into the living room of your house. Such a generator might produce as much as 1,000,000 watts of output power. This is enough power for an entire community.

Figure 1-9 shows an extremely large AC generator, next to the man, that is powered by the large turbines on the right. This generating system produces up to 609,000 kilowatts of output power. It is just one type of AC generator that is used by electric power companies to generate electrical power for homes and industry. Other systems can generate as much as 1,000,000 kilowatts of power.

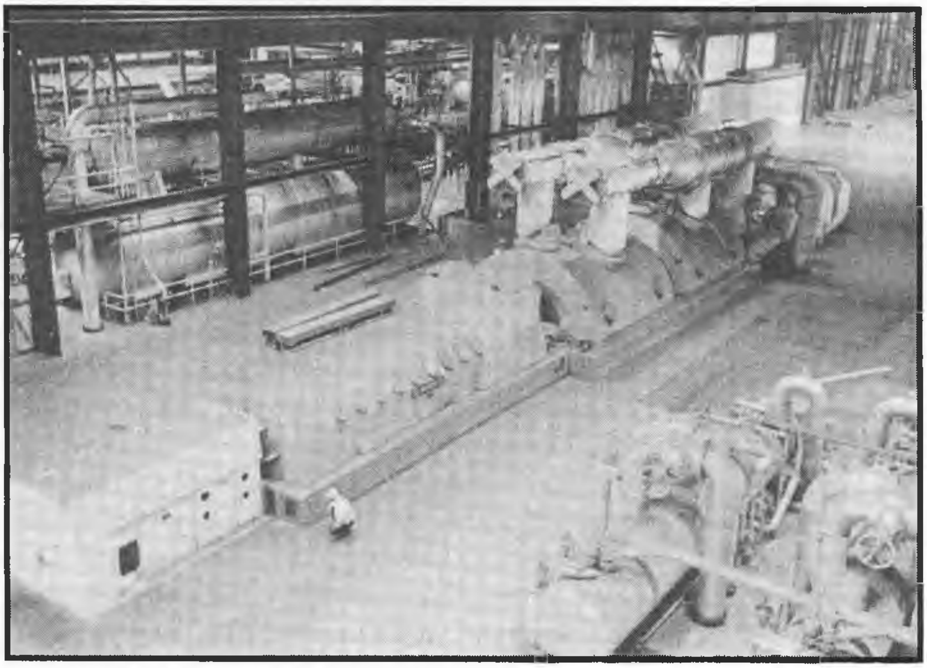


Figure 1-9
An extremely large AC generator.

Programmed Review

15. A voltage is induced into a wire that cuts through magnetic lines of force. This action is commonly referred to as electromagnetic ___________.

16. (induction) The induced voltage results because the cutting action of the magnetic lines of force causes the free electrons in the ____________ to move.

17. (conductor) The free electrons move towards one end of the conductor which produces an excess of electrons at one end of the conductor and a deficiency at the other end. This excess and deficiency of electrons create a difference of potential or ___________.

18. (voltage) The polarity of the voltage induced within the moving conductor is determined by the direction of conductor motion and the direction of the magnetic ___________.

19. (field or lines of force) The amount of voltage induced into a conductor is affected by the strength of the magnetic field. If the magnetic field becomes stronger, the induced voltage will ___________.

20. (increase) The induced voltage is also affected by the speed of conductor movement. If there is an increase in the speed of movement, there will also be an increase in the induced ___________.

21. (voltage) The length of the conductor within the magnetic field also affects the induced voltage. If the length of the conductor increases, the induced voltage will also ___________.

22. (increase) The induced voltage also varies with the angle at which the conductor cuts the magnetic lines of force. As this angle varies from zero to a maximum of 90°, the induced voltage increases from zero to its ___________ value.

23. (maximum) When you consider the various factors which affect the induced voltage, there is one simple rule takes these factors into account. This rule states that the induced voltage is directly proportional to the rate at which the conductor cuts the magnetic ____________ .

24. (lines of force or field) A conductor may be shaped into the form of a loop and rotated within a magnetic field to produce a voltage that varies in both value and direction. Such an arrangement produces a device known as an _________ generator.

25. (AC) The AC generator's rotating loop is called an armature and the magnet that is used to provide the magnetic field for the device is called a field magnet. The armature must rotate constantly within the __________ __________ in order to produce an output voltage.

26. (magnetic field) Since the armature must constantly rotate, it is impossible to permanently connect any wires or leads to the ends of the armature loop. Therefore two metal slip rings are attached to the wire ends and are aligned so that they slide against two brushes which remain stationary. An external load may be connected directly to these __________ .

27. (brushes) One side of the armature loop always moves in the opposite direction to the other side. This means that the voltage induced into each side of the loop is opposite in __________ .

28. (polarity) Although they are opposite in polarity, the voltages induced into each side of the armature are series-aiding. This means that the output voltage which appears at the brushes is equal to the sum of the voltages induced into each side of the

29. (armature or loop) If the armature begins its rotation at a point where its sides are moving parallel to the magnetic lines of force and rotates one-half revolution so that its sides again move parallel to the lines of force, the armature cuts lines of force at a rate which vary from zero to some maximum value and back to zero. During this one-half revolution, the voltage induced into the armature varies from __________ to __________ and back to __________ .

30. (zero, maximum, zero) If the armature rotates another one-half revolution, it again cuts lines of force just as it did during the first one-half revolution. However, during this half of the revolution, the armature cuts across the lines of force in the opposite direction. This means that the induced voltage varies as it did before, but this time it has the opposite ____________ .

31. (polarity) One complete revolution of the armature therefore produces an AC voltage which varies both in __________ and ___________ .

32. (value and direction) The armature within an AC generator must rotate constantly in order to produce a continuous AC output voltage. When a load is connected to the generator, an output load current results. However, even when no load current is drawn from the generator, an output AC ___________ is still produced.

33. (voltage)

THE SINUSOIDAL WAVEFORM

In the previous section you learned how an AC voltage could be produced by a simple AC generator. This AC voltage was graphically plotted in Figure 1-8 so that you could see exactly how it varies throughout one complete revolution of the generator's armature. When voltage (or current) values are plotted to form a continuous curve, they form a picture or pattern which is referred to as a waveform. The waveform shows exactly how the voltage varies over a period of time as the armature rotates. You may examine the waveform to determine the exact value and polarity of the AC voltage at any particular instant when the armature is at a specific point.

The waveform shown in Figure 1-8 varies in a unique manner and is given a special name. It is called a sinusoidal waveform or simply a sine wave. The sine wave is the most basic and widely used AC waveform. It can be produced by an AC generator as previously shown or it can be produced by various types of electronic circuits.

The AC voltage that you use in your home to provide heat, light, and operate appliances, varies in a sinusoidal manner. The radio and television signals which carry sound and picture information are basically sine waves whose characteristics have been modified. A variety of waveforms that are more complex than the basic sine wave can be proven to be mathematically equivalent to combinations of sine waves.

The Basic Sine Wave

The sine wave is referred to as a sine wave because it changes in value according to the trigonometric function known as sine. Sine is a trigonometric function that describes the relationship between the sides of a right triangle. A right triangle is a triangle in which one of the angles equals 90 degrees. A triangle is defined as a three-sided figure that contains 3 angles. The sum total of all three angles in a triangle is 180 degrees.

An angle has a sine value that is equal to the ratio of the length of the opposite side (the side opposite the working angle) to the length of the hypotenuse (the side opposite the right angle). This relationship is shown in Figure 1-10. Note that the sine of angle A is equal to the opposite side (side Y) divided by the hypotenuse (side Z). Angle B has a sine value that is equal to its opposite side (side X) divided by the hypotenuse (side Z). Note also that the hypotenuse is always larger than either of the other sides. Therefore, the value of the sine varies from () to 1, for angles between zero and 90 degrees.

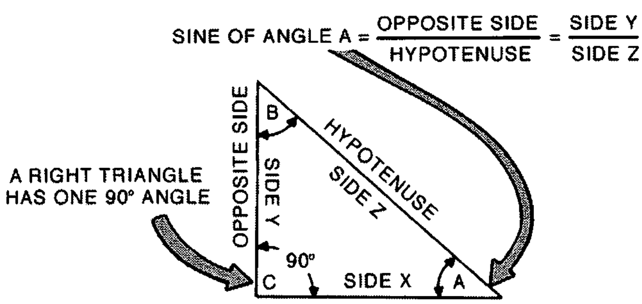


Figure 1-10
The sine function.

The sine of angle A (or angle B) varies as the angle varies. This is because the length of the opposite side and the length of the hypotenuse both change as the angle changes. Angle A or angle B can be any value between 0 degrees and 90 degrees. These are the extreme limits which can occur within the right triangle. Remember, the sum of angles A, B, and C must always equal 180 degrees.

As angle A (or B) varies from a minimum of 0 degrees to a maximum of 90 degrees, its sine value varies from zero (when side Y is infinitely small) to 1 (when side Y and size Z are equal). The various sine values for all of the angles between 0 degrees and 90 degrees (in increments of 1 degree) are shown in Figure 1-11. This table of sine values is a portion of the standard table of trigonometric functions. You can find these functions in almost any textbook on trigonometry.

Angle	Sine	Angle	Sine	Angle	Sine
0°	0.000	31°	.515	61°	.875
1°	.018	32°	.530	62°	.883
2°	.035	33°	.545	63°	.891
3°	.052	34°	.559	64°	.899
4°	.070	35°	.574	65°	.906
5°	.087				
6°	.105	36°	.558	66°	.914
7°	.122	37°	.602	67°	.921
8°	.139	38°	.616	68°	.927
9°	.156	39°	.629	69°	.934
10°	.174	40°	.643	70°	.940
11°	.191	41°	.656	71°	.946
12°	.208	42°	.669	72°	.951
13°	.225	43°	.682	73°	.956
14°	.242	44°	.695	74°	.961
15°	.259	45°	.707	75°	.966
16°	.276	46°	.719	76°	.970
17°	.292	47°	.731	77°	.974
18°	.309	48°	.743	78°	.978
19°	.326	49°	.755	79°	.982
20°	.342	50 °	.766	80°	.985
21°	.358	51°	.777	81°	.988
22°	.375	52°	.788	82°	.990
23°	.391	53°	.799	83°	.993
24°	.407	54°	.809	84°	.995
25°	.423	55°	.819	85°	.996
26°	.438	56°	.829	86°	.998
27°	.454	57°	.830	87°	.999
28°	.470	58°	.848	88°	.999
29°	.485	59°	.857	89°	1.000
30°	.500	60°	.866	90°	1.000

Figure 1-11
A table of sine waves for angles between 0° and 90°.

How does this apply to the voltage output from an AC generator? As you know, the output voltage from an AC generator varies in a sinusoidal manner. Figure 1-12A is a representation of the output of an AC generator 30 degrees through the armature's rotation. In this illustration, the maximum output voltage for the generator is shown as the hypotenuse of the right triangle, 100 volts. The actual output voltage, at any instant, is represented by the length of the side opposite the angle of rotation.

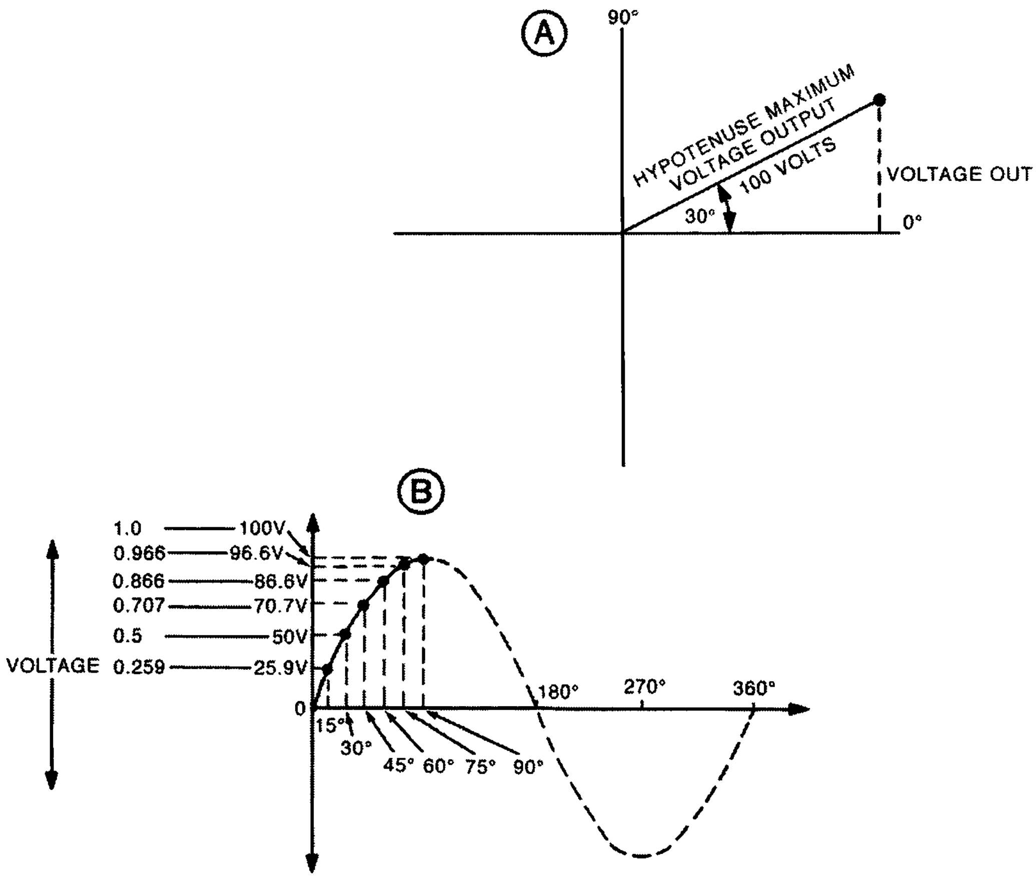


Figure 1-12
The sine wave varies according to the sine function between 0° and 90°.

Since the sine of any angle is the relationship of the opposite side divided by the hypotenuse, you can determine the output voltage of the generator, 30 degrees through the armature's rotation. To do this, multiply the length of the hypotenuse (100 volts) by the sine of 30 degrees (.5). In this case, the output voltage of the generator, 30 degrees through the armature's rotation, is 50 volts.

Figure 1-12B illustrates values for a number of armature positions. Note that specific voltage values are shown at 15-degree intervals, between 0 degrees and 90 degrees, along the horizontal base line. Keep in mind that the horizontal line indicates the number of degrees of armature rotation.

The voltage is zero at the beginning of the waveform when the armature is at 0 degrees (parallel to the field). When the armature rotates 15 degrees, the voltage increases to a value equal to the sine of 15 degrees (.259) times the generator's maximum output voltage. Therefore, the output voltage after 15 degrees of rotation is 25.9 volts.

The output voltage continues to rise for the first 90 degrees of rotation. The sign of the angles along with the voltages present at the output are shown in Figure 1-12B. At 30 degrees, the output is 50 volts; at 45 degrees, the output is 70.7 volts, and so on. At 90 degrees, the sine of the angle is 1 and the voltage output at this time is the maximum voltage output for the generator.

When you compare the angular position of the armature with the corresponding output voltage, you find that the voltage increases according to the sine of the angle of rotation.

Between the 90 and 180 degree points on the waveform, the voltage drops from its maximum value to zero. During this portion of the waveform, the voltage decreases in the exact opposite way that it increased. In other words, the sine is maximum at 90 degrees and decreases to zero at 180 degrees. Between the 180 and 360 degree points, the voltage varies in the same way as it did between 0 degrees and 180 degrees. The only difference is that the polarity of the voltage is opposite. This is why the curve extends below the horizontal line.

The positive alternation of the waveform is from 0 to 180 degrees, while the negative alternation is from 180 to 360 degrees. The positive and negative alternations make up one complete sine wave. The time of one complete sine wave (cycle) is the waveforms period.

The Cycle

Each time the armature of an AC generator rotates through one complete revolution, it generates an output voltage that increases and decreases in value in first one direction and then in the opposite direction, as shown in Figure 1-13. When the armature rotates one complete revolution, it completes one cycle of events. In other words, it produces one complete change in voltage values. If the armature rotates another 360 degrees, it simply repeats the cycle or sequence of output voltages. The output voltage produced during one complete revolution of the armature is therefore referred to as *one cycle* of output voltage as indicated in Figure 1-13. The armature also produces one cycle of output current when there is a complete circuit through which current can flow.

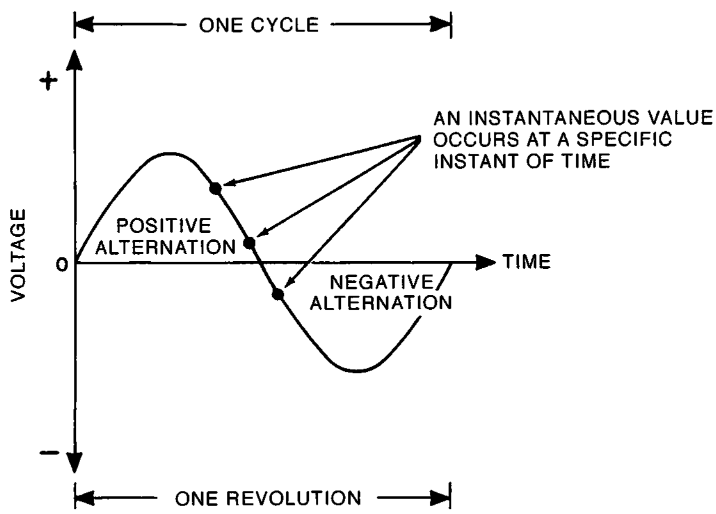


Figure 1-13
One revolution of the armature produces one cycle of output voltage.

During the generation of one cycle of output voltage, there are two changes or alternations in the polarity of the voltage. In other words, the voltage has one polarity during the first half of the cycle and the opposite polarity during the second half. These equal but opposite halves of a complete cycle are referred to as *alternations*. To further distinguish one-half of the cycle (or one alternation) from the other, one alternation is generally called the *positive alternation* while the other alternation is called the *negative alternation*. These two alternations are identified in Figure 1-13. The terms positive and negative are used arbitrarily to distinguish one alternation from the other. During the positive alternation, the output voltage has a specific polarity, and during the negative alternation the polarity of the voltage is reversed.

The voltage sine wave in Figure 1-13 is made up of an infinite number of voltage values which have been plotted and joined together. At any particular point on the waveform, the voltage is generally referred to as an *instantaneous* value, a value that occurs at a specific instant of time.

The instantaneous value is equal to the maximum value times the sine of the angle, at any instant. You may recognize this equation from the previous discussion of the sine wave.

It takes a specific amount of time to generate the sine wave shown in Figure 1-13. For this reason, you can think of the horizontal line on which the waveform is plotted as a time line, or a time base. The horizontal line may be calibrated in units of time or degrees of armature rotation.

The horizontal line in Figure 1-13 also serves as a zero reference line. Any voltage value that is plotted on this line has a value of zero. Assume all values above the line to be positive. Assume all values below the line to be negative. Therefore, all of the instantaneous voltage values which make up the positive alternation have positive values, and all of the instantaneous values which form the negative alternation have negative values. This is indicated by the plus (+) and minus (–) signs on the vertical axis of the graph shown in Figure 1-13.

The terms described in this discussion are extremely important. If you want to understand AC electronics, you must become familiar with them. These terms describe the various characteristics of one cycle of a sine wave. You must under stand the exact meaning of these terms, since they are used throughout your study of electronics.

Note that the sine wave shown in Figure 1-13 could represent one complete cycle of output current as well as a cycle of output voltage. When current is represented, the positive and negative alternations represent current that is flowing in first one direction and then the opposite direction.

Programmed Review

34. The exact manner in which a voltage or current varies over a period of time can be graphically represented by plotting a large number of voltage or current values over a period of time to form a continuous curve. Such a curve serves as a picture or pattern and is called a ________ .
35. (waveform) The output voltage produced by an AC generator varies in value according to the trigonometric function known as the sine. The output voltage waveform is therefore referred to as a ________ wave.
36. (sine) One half of a revolution of the generator's armature produces a voltage that increases to a maximum value and then drops back to zero. The voltage actually rises from zero to maximum according to the sine function, but it decreases from maximum to zero in the exact ________ manner.
37. (opposite) During the second half of the revolution, the armature produces a voltage which again rises to maximum and drops to zero as it did before. However, this time the voltage has the opposite ________ .
38. (polarity) Each time the armature makes one complete revolution (360°), it completes one cycle of events and produces one ________ of output voltage.
39. (cycle) Throughout one half of the cycle, the voltage has one polarity as it varies from zero to maximum and back to zero. Then during the other half of the cycle, the voltage has the opposite polarity as it varies in the same manner. Since the polarity of the voltage changes or alternates during the cycle, the two halves of the cycle are called ________ .

40. (alternations) One half of the AC cycle is referred to as the ___________ alternation.

41. (positive) The other half of the cycle is called the ___________ alternation.

42. (negative) Any AC sine wave is assumed to be made up of an infinite number of values which occur at specific instants of time. The value at any specific instant of time is called an _______________ value.

43. (instantaneous) The AC sine wave may be plotted above or below a horizontal line or axis which is calibrated in degrees of armature rotation. Because the sine wave is generated over a period of time, it is possible to plot its instantaneous values along a horizontal line which is calibrated in units of _________ .

44. (time) Any value which is plotted directly on the horizontal line has a value of _________ .

45. (zero) All of the instantaneous values plotted above the horizontal line are assumed to be positive values. These are the values that are used to form the ___________ alternation.

46. (positive) The values plotted below the horizontal line have negative values and are used to plot the ____________ alternation.

47. (negative)

AC VALUES

Since the value of a sine wave of voltage or current continually changes, you must be specific when you describe the value of the waveform. In other words, you cannot simply state that a voltage sine wave has a value of 100 volts. You must specify that this is the maximum value of the voltage waveform, or some value at a specific point between zero and maximum. There are several ways to express the value of a sine wave and you must be familiar with each of them.

Peak Value

Each alternation of a sine wave is made up of an infinite number of instantaneous values. These values are plotted at various heights above and below the horizontal line to form a continuous waveform. It is the height, amplitude, of each instantaneous value above or below the line that represents the sine wave's actual value. The greater the amplitude, the higher the value. The points on the waveform which have the greatest height, or distance from the horizontal line, are defined as *peak* values.

The two peak values in one cycle of a sine wave are clearly shown in Figure 1-14. One peak occurs during the positive alternation when the waveform reaches its maximum height. This point is appropriately identified as the *positive peak value* and it represents the maximum positive value that occurs during one cycle. The second peak value occurs during the negative alternation when the wave form again reaches its maximum height, but this time the peak is below the line. This point is referred to as the *negative peak value.*

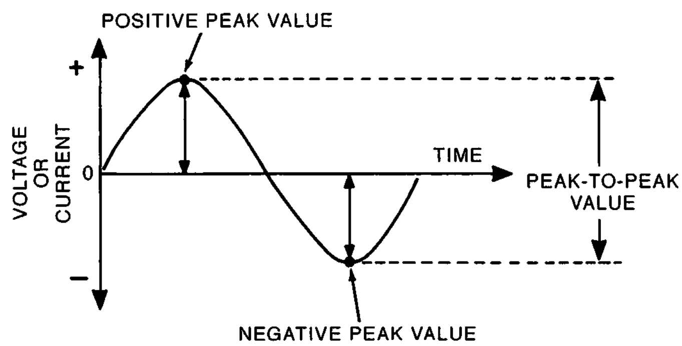


Figure 1-14
Peak and peak-to-peak values.

The positive and negative peak values of a sine wave are equal in value. In other words, the positive and negative peaks are an equal distance from the zero reference line and require the same amount of time to generate. For example, a volt age sine wave which has a positive peak value of +5 volts, has a negative peak value of –5 volts, and the widths of the alternations are the same. Only the polarity of the voltage is different and is indicated by the + and – signs. The same relationship is also true for a sine wave of current. The peak value of the current during the positive alternation is equal to the peak value during the negative alternation. The only difference is that current flows in opposite directions on the positive and negative alternations.

Peak values are sometimes described by other terms which have the same meaning. For example, the peak value is sometimes called the *peak amplitude* or the *maximum amplitude*. Furthermore, all of these terms apply to any type of waveform. These terms are not limited to the sinusoidal waveform that you are examining at this time.

Peak-To-Peak Value

Sometimes it is necessary to know the total height or value of a sine wave. The overall value of the sine wave (from one peak to the other) is called its *peak-to peak value*. The peak-to-peak value of a sine wave is indicated in Figure 1-14.

To determine the peak-to-peak value, you add the positive and negative peak values. Since two peaks are equal in value, you need to know only one peak value. Simply multiply the peak value by 2 to determine the peak-to-peak value. This relationship is shown mathematically as follows:

$$\text{peak-to-peak value} = 2 \times \text{peak value}$$

For example, if the peak value of a voltage sine wave is 5 volts, the peak-to-peak value must be equal to 2 x 5 volts or 10 volts. A current sine wave with a peak value of 10 amperes has a peak-to-peak value that is equal to 2 × 10 amperes or 20 amperes. In the case of voltage, the difference of potential is 10 volts and the peaks are labeled +5 volts and –5 volts.

To determine peak value, when you know the peak-to-peak value, simply divide the peak-to-peak value by 2. For example, a sine wave with a peak-to-peak value of 18 volts has a peak value of 1 8V/2 or 9 volts. A current sine wave with a peak to-peak value of 5 amperes has a peak value of 5A/2 or 2.5 amperes.

It is necessary to understand the meaning and relationship of the peak and peak to-peak values of a voltage or current sine wave. You will need these values, often when you analyze the characteristics of waveforms, and when you measure waveforms. Various test instruments such as oscilloscopes and certain types of AC meters are used to directly measure the peak-to-peak value of a waveform.

The oscilloscope is the most common instrument to measure peak-to-peak values. The oscilloscope measures the value of the peaks, and displays them on its vertical axis. The vertical axis is divided into squares, each square is 1 centimeter wide and 1 centimeter high. Each square (CM) represents a specific amplitude. The oscilloscope also contains a vertical range switch (V/CM). The V/CM range switch changes the values of the squares on the vertical axis. The range switch expands or decreases the space required to display a waveform.

The oscilloscope can display an AC waveform above and below the zero reference line. To do this, you select AC coupling. The coupling switch can be set to reference AC, DC, or ground on most oscilloscopes. In the AC position, the sine wave is displayed with the center line on the scope as the zero reference line. The positive and negative alternations then appear above and below the reference.

An oscilloscope is also capable of displaying the time of a waveform. Remember that the time of a waveform is defined as its period, and is the combined time of the positive and negative alternations. Time is displayed on the horizontal axis and is controlled by a TIME/CM switch. The horizontal squares are 1 square centimeter, and are used to expand or compact the waveform in terms of the space required to display the time of one cycle. The TIME/CM function provides a variable horizontal time base reference line.

When you use the vertical and horizontal squares together, it is possible to measure and observe the complete waveform and evaluate any point on the waveform in terms of amplitude (value) and time. This allows you to measure a waveform's period, peak, and peak-to-peak values. You can also measure the rate of change in amplitude as time increases. The oscilloscope allows you to see the actual waveform. This is especially valuable when you learn about phase and distortion later in your studies. At this time, you are only concerned with amplitude, time, and the rate of change.

Average Value

When you examine one alternation of a voltage or current sine wave, you find that it increases from zero to a peak value and back to zero as shown in Figure 1-15. The voltage or current remains at its peak value for only an instant. Except for this one instant of time, the voltage or current is always lower than its peak value. Since the voltage or current remains at the peak value for only an instant, the average voltage for the entire alternation must be less than the peak value. To determine this average voltage, take a large number of the instantaneous values, which occur during one alternation, and compute their average value. You can also use integral calculus to calculate the average. Integral calculus is the branch of mathematics that is used to find volumes, areas, and equations of curves. In either case, you will find that the average value of one alternation is approximately equal to 0.636 of its maximum or peak value. The relationship between peak and average is shown in Figure 1-15 and is expressed by the following equation:

$$\text{average value} = 0.636 \times \text{peak value}$$

For example, a voltage sine wave which has a peak value of 100 volts has an average value of 0.636 x 100 V or 63.6 volts. This equation determines the average value of either a voltage or current sine wave. For example, a current sine wave with a peak value of 1() amperes has an average value of 0.636 × 10 A or 6.36 amperes.

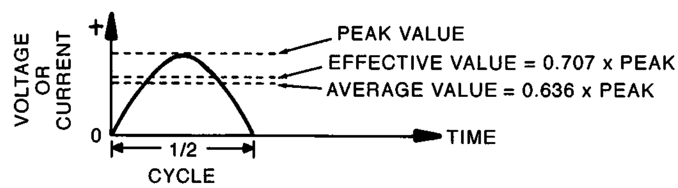


Figure 1-15
Average and effective values.

You can also transpose the above equation so to determine the peak value, when you know the average value. In this case, the equation becomes:

$$\text{peak value} = \frac{\text{average value}}{0.636}$$

Suppose the average value of a voltage sine wave is 50 volts. Its peak value is 50 V/0.636 or 78.6 volts. A current sine wave, with an average value of 1 ampere, has a peak value of 1 A/0.636 or 1.57 amperes.

It is important to note that you have considered the average value of only one alternation or one-half cycle; you must add the average value of one alternation to the average value of the other alternation. Since each alternation has the same average value (0.636 × peak value) and because one value is positive when the other is negative, you can see that the two averages cancel. Therefore, the average value of a sine wave is zero.

Whenever the average value of a sine wave is described, it is common practice to assume that the description concerns only one of the alternations. The true average of a sine wave (zero) is most commonly referred to as the sine wave's reference line.

Average values are not used extensively when you deal with voltage and current sine waves, but they do have certain special applications. As you proceed with your study of AC Electronics, you will find it beneficial to know how to determine these average values.

Effective Value

When direct current (DC) flows through a resistor, a certain amount of power is dissipated by the resistor in the form of heat. A certain amount of heat is also produced if an alternating current flows through the same resistance. However, the heat produced by an alternating current, with a peak value of 1 ampere, is not as great as the heat produced by a DC current of 1 ampere. The alternating current produces less heat because it stays at its peak value of 1 ampere for only a short period of time. Therefore, you must use an alternating current with a peak value higher than 1 ampere to produce the same amount of heat that is produced by 1 ampere of direct current.

The AC current that produces the same amount of heat in a specified resistance as a DC current that has a value of 1 ampere has an effective value of 1 ampere. In other words, a DC current of 1 ampere is equivalent to an AC current which has an effective value of 1 ampere, as far as their ability to produce heat is concerned. For this reason, the AC current must have a peak value higher than 1 ampere, in order to be equivalent to the DC current.

You can determine the effective value of a sine wave of current with a mathematical process known as the root-mean-square or rms value. The rms method is lengthy and will not be examined at this time. However, you can use this process to show that the effective value of a sine wave of current is equal to 0.707 times its peak value. The relationship between peak and effective values of a sine wave is shown in Figure 1-15. The same relationship is shown in the following equation:

$$\text{effective value} = 0.707 \times \text{peak value}$$

For example, a current sine wave with a peak value of 10 amperes has an effective value of 0.707 × 10 A or 7.07 amperes. This AC current, which has a peak value of 10 amperes, produces the same heating effect as a direct current of 7.07 amperes.

Since an AC current is produced by an AC voltage, you may express the AC voltage in terms of its effective value. You can use the equation (0.707 × peak value) to determine the effective value of a voltage sine wave. For example, a voltage sine wave with a peak value of 40 volts has an effective value of 0.707 equation (0.707 × peak value) 40 V or 28.28 volts.

Most AC voltmeters like the one shown in Figure 1-16 are calibrated to measure effective (rms) values. They measure only one alternation's effective voltage. The AC voltmeter shown is a special type meter that is used to monitor line voltage. This AC voltmeter is used to continuously monitor the 120-volt AC voltage that is present in most homes. It is calibrated to read the effective or rms value of an AC sine wave. It can be plugged into any convenient electrical outlet. Note that there are no meter leads. It is a special purpose meter and has very limited uses. The peak-to-peak AC voltmeter is also considered to be a special purpose voltmeter. The more common voltmeters are used to measure effective voltage. They have test leads so that the difference of potential between two points can be measured. The more common AC meters are multi-function meters. That means that they have selectable ranges and functions, such as measuring voltage, current, and resistance that have a variety of values. This type of meter can be either a VOM or an electronic type.

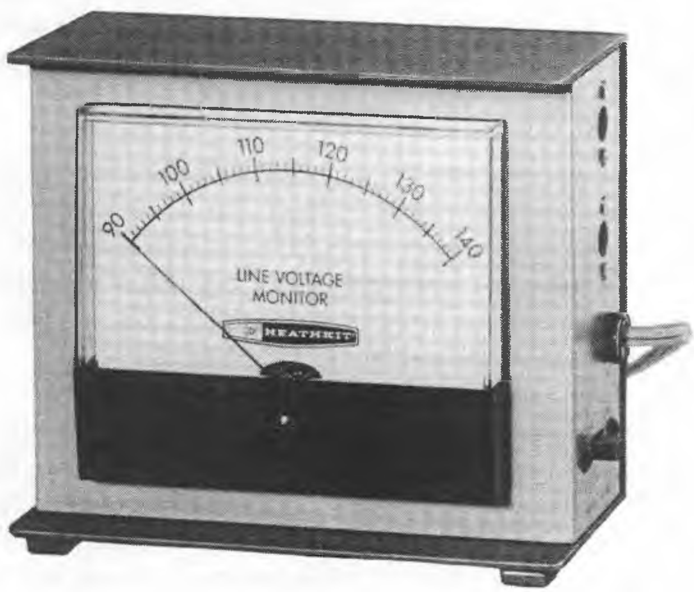


Figure 1-16
An AC voltmeter to measure the
120-volt AC voltage in the home.

You can use the following equation to determine the peak value of a sine wave when you know effective value:

$$\text{peak value} = 1.414 \times \text{effective value}$$

The number (1.414) is the reciprocal of 0.707, and 0.707 is the number you use to change peak values to effective (rms) values.

You can use this equation to determine the peak value of either a current sine wave or a voltage sine wave. For example, a current sine wave with an effective value of 7 amperes has a peak value of 1.414×7 A or approximately 10 amperes. A voltage sine wave with an effective value of 30 volts has a peak value of 1.414×30 V or 42.4 volts.

You will use effective (or rms) values extensively when you work with AC sine waves. It is important that you understand the relationship between effective and peak values of a sine wave. In most cases, when an AC voltage or current is specified, it is the effective value that is specified. In fact, effective values are used so extensively that they are often not specifically identified. For example, it is common practice to express an effective voltage value of 100 volts as simply 100 volts AC or an effective current value of 10 amperes as simply 10 amperes AC. When the alternating current or voltage value is specified, but not specifically identified, the effective value is usually implied. For example, the 120-volt AC electrical power that is used in your home has an effective value of 120 volts, and its peak value is approximately 170 volts.

Most AC voltmeters and ammeters are calibrated to read effective (rms) values. The ability to accurately measure these effective values is very important, since the effective values are most often used in AC calculations.

Period

When you analyze an AC sine wave, it is often necessary to know exactly how much time is required to generate one complete cycle. The time required to produce one complete cycle is called the *period* of the waveform. The period of a sine wave is shown in Figure 1-17. The period is usually measured in seconds although other units of time can be used. Furthermore, the period is often represented by the letter T as shown.

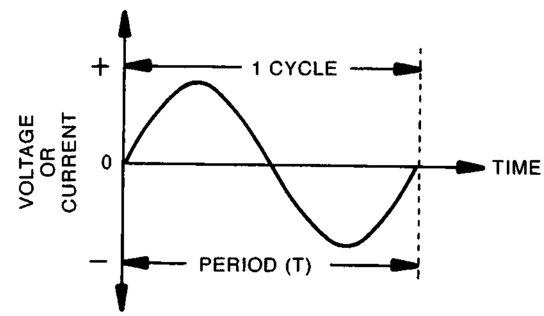


Figure 1-17
The period of a sine wave.

If a generator produces 1 cycle of output voltage in 1 second, the output sine wave has a period of 1 second. However, if 4 cycles are produced in 1 second, the output sine wave has a period of 1/4 of a second (T = 0.25 seconds). Remember, that the period is the time of one cycle, and not the total time required to generate a given number of cycles.

Time of a cycle is also expressed in angular notation. Remember that an armature rotates through 360 degrees to produce a complete sine wave. It started at zero and increased to maximum at 90 degrees. This portion of one revolution is equal to 1/4 of one revolution. From maximum back to zero completes one alternation which is 1/2 of one cycle, while the other 1/2 cycle is the other alternation.

Angular motion is measured in radians. A radian is equal to approximately 57.3 (57.295317254) degrees, and a circle (360 degrees) contains exactly 2 π radians.

Since Pi (π) is a constant that is used in electronic calculations and is equal to 3.141618,

$$2\pi \text{ radians} = 360$$
$$(2)\ (3.141618)\ (57.295317254) = 360$$

For your purposes, you can round π off to 3.14. Then, (2) (3.14) (57.3) = 359.844. As you can see, it is not exactly equal to 360. However, both pi and radians have been rounded off.

Now that you have some of the basics for angular measurements, you can learn about angular velocity. In AC, the term most often used for rate of change is frequency.

Frequency

It is often necessary to know how rapidly an AC waveform changes in value. In other words, it may be important to know how many cycles of the waveform occur in a given period of time. The number of cycles that occur in a specified period of time is called the *frequency* of the waveform.

Each time the armature of the simple AC generator completes one revolution, one cycle is produced. This means that the frequency of an AC waveform is determined by the speed at which the armature rotates. As the speed of rotation increases, more cycles are generated for each unit of time. Therefore, the frequency increases.

The frequency of an AC sine wave is usually expressed in terms of the number of cycles generated per second. For example, an armature that rotates 1 complete revolution each second produces 1 cycle of AC each second. The AC voltage has a frequency of 1 cycle per second.

Although the frequency is the number of cycles produced each second, it is expressed in *hertz* (abbreviated Hz). A generator which produces an AC voltage that completes 1 cycle per second, operates at a frequency of 1 hertz. The term hertz is simply used in place of cycles per second.

If the AC generator produces 30 cycles of AC output voltage each second, it operates at a frequency of 30 hertz or 30 Hz. Likewise, an output of 60 cycles each second is expressed as 60 hertz or 60 Hz.

There is a definite relationship between the frequency and the period of a sine wave. When the period of a sine wave is equal to 1 second, the frequency is equal to 1 hertz as shown in Figure 1-18. If the period decreases to 0.5 seconds or one-half of its original value, the frequency doubles or increases to 2 hertz. This is because exactly twice as many cycles occur each second. Likewise, if the period doubles, the frequency is cut in half.

Frequency is the reciprocal of time. The following equation shows this relationship:

$$f = \frac{1}{T}$$

This equation simply states that frequency, represented by the letter f, is equal to 1 divided by the period, T. Furthermore, if the period is expressed in seconds, the frequency is in hertz. For example, when the period of a sine wave is equal to 0.05 seconds, the frequency of the waveform is equal to:

$$f = \frac{1}{0.05} = 20 \text{ hertz}$$

A period of 0.05 seconds therefore corresponds to a frequency of 20 hertz. However, if the period is cut in half or reduced to 0.025 seconds, the frequency is:

$$f = \frac{1}{0.025} = 40 \text{ hertz}$$

In other words, the frequency increases to 40 hertz or doubles. The equation shows that f and T are inversely proportional. When one increases, the other decreases proportionally.

To determine T when you know f, transpose the equation like this:

$$T = \frac{1}{f}$$

The equation states that T is equal to 1 divided by f. If f is expressed in hertz, the value of T is in seconds. For example, when f is equal to 100 hertz, T is determined as follows:

$$T = \frac{1}{100 \text{ Hz}} \text{ or } 0.01 \text{ seconds}$$

The period (T) is equal to 0.01 seconds or 10 ms.

Frequencies that range from just a few hertz to many millions of hertz are widely used in the electronics industry. For example, the 120-volt AC electrical power used in your home has a frequency of 60 hertz. This 60 hertz power operates your lights and appliances and it may even provide heat. Many electronic applications require much higher frequencies. This is because high frequencies are needed to carry information or intelligence. The higher frequencies are easier to convert into electromagnetic (radio) waves. The higher frequencies can be transmitted more easily over long distances.

You cannot produce these higher frequencies with mechanical AC generators. Mechanical generators cannot rotate at the very high speeds required to produce frequencies such as 10 kHz. To produce a frequency of 10 kHz requires a waveform with a period of 1 divided by 10,000. The generator would have to turn at the rate of 600,000 revolutions per minute (RPM). Therefore, electronic generators are used to produce the required high frequencies which are necessary. Electronic circuits do not require moving parts and are capable of easily producing frequencies many times greater than 10 kHz.

When you work with frequencies that extend up to many millions of hertz, you must work with very large numbers. However, you can use various metric prefixes and positional notation (powers of ten) to reduce these large numbers to a manageable size. The metric prefixes most commonly used for this purpose are shown in Table 1-1.

Table 1-1

Metric Prefix	Symbol	Powers of Ten Value
kilo	k	1000 (10^3)
mega	M	1,000,000 (10^6)
giga	G	1,000,000,000 (10^9)
milli	m	.001 (10^{-3})
micro	μ	.000,001 (10^{-6})
pico	p	.000,000,000,001 (10^{-12})

Negative prefixes are included in the table because they are commonly used in electronics. However, the negative prefixes are not used to represent frequency. Remember, time and frequency are closely related.

You can place a prefix before a word to change its meaning. For example, the prefix kilo means 1,000 and when you place it before the word hertz, you obtain the word kilohertz which means 1,000 hertz. Generally you express 1,000 hertz as simply 1 kilohertz or you use the symbol k to represent kilo and the symbol Hz to represent hertz and express the quantity as 1 kHz. In a similar manner, you use mega (M) to represent 1,000,000. Therefore, you can express 1,000,000 hertz as 1 megahertz or 1 MHz. The prefix giga (G) represents 1,000,000,000. Therefore, you can express 1,000,000,000 hertz as 1 gigahertz or 1 GHz. Also, a frequency of 10,000 hertz could be expressed as 10 kilohertz, or a frequency of 1,000,000,000 hertz could be expressed as 1,000 megahertz.

The frequencies that are most commonly used in electronic applications are shown in Figure 1-19. As shown in this Figure, the frequencies between 15 hertz and 300 GHz (300,000,000,000 hertz) are most widely used. The frequencies between 15 hertz and 20 kHz (20,000 hertz) are referred to as audio frequencies (AF) as shown. The AC current that has a frequency in this range produces an audible tone to which the human ear responds. In many cases, the AC current must be applied to a device, such as a speaker, which converts the AC waveform into sound waves that can be detected by the human ear.

The frequencies between 3 kHz (3,000 hertz) and 300 GHz are referred to as radio frequencies (RF) since they are used extensively in radio communications. This band of frequencies is further divided into eight smaller bands. The band with the lowest frequencies is called the very low frequency (VLF) band and each higher band is appropriately named. The highest band is called the extremely high frequency (EHF) band. Frequencies within the various RF bands are widely used to transmit information or intelligence from one location to another. Once these frequencies are produced, in the form of electrical currents and voltages, they are converted to radio waves which are suitable for transmission through space.

The frequencies within the eight RF bands are further divided into smaller bands which are allocated for specific applications. As shown in Figure 1-19, a small band of frequencies within the medium frequency (MF) band is identified as the standard broadcast band. This band of frequencies is used by commercial AM radio stations. Also note, that the television channels (2 through 6 and 7 through 13) and the FM band (used by FM radio stations) are within the very-high frequency (VHF) band. The higher television channels (14 through 83) are transmitted at higher frequencies which fall within the ultra-high frequency (UHF) band. These various frequency assignments (as well as others which have not been discussed) are controlled by an agency of the U.S. Government known as the Federal Communications Commission (FCC).

It is possible to produce frequencies which are higher or lower than those shown in Figure 1-19. However, above the upper RF limit (300 GHz), the characteristics of AC signals change considerably and they are no longer suitable for transmission through a wire or in the form of radio waves. Above this upper limit are other forms of electrical energy such as light waves, x-rays, and cosmic rays. Scientists assume that these various forms of energy occur as specified frequencies, even though they have many additional characteristics which cannot be explained by conventional electronic theory.

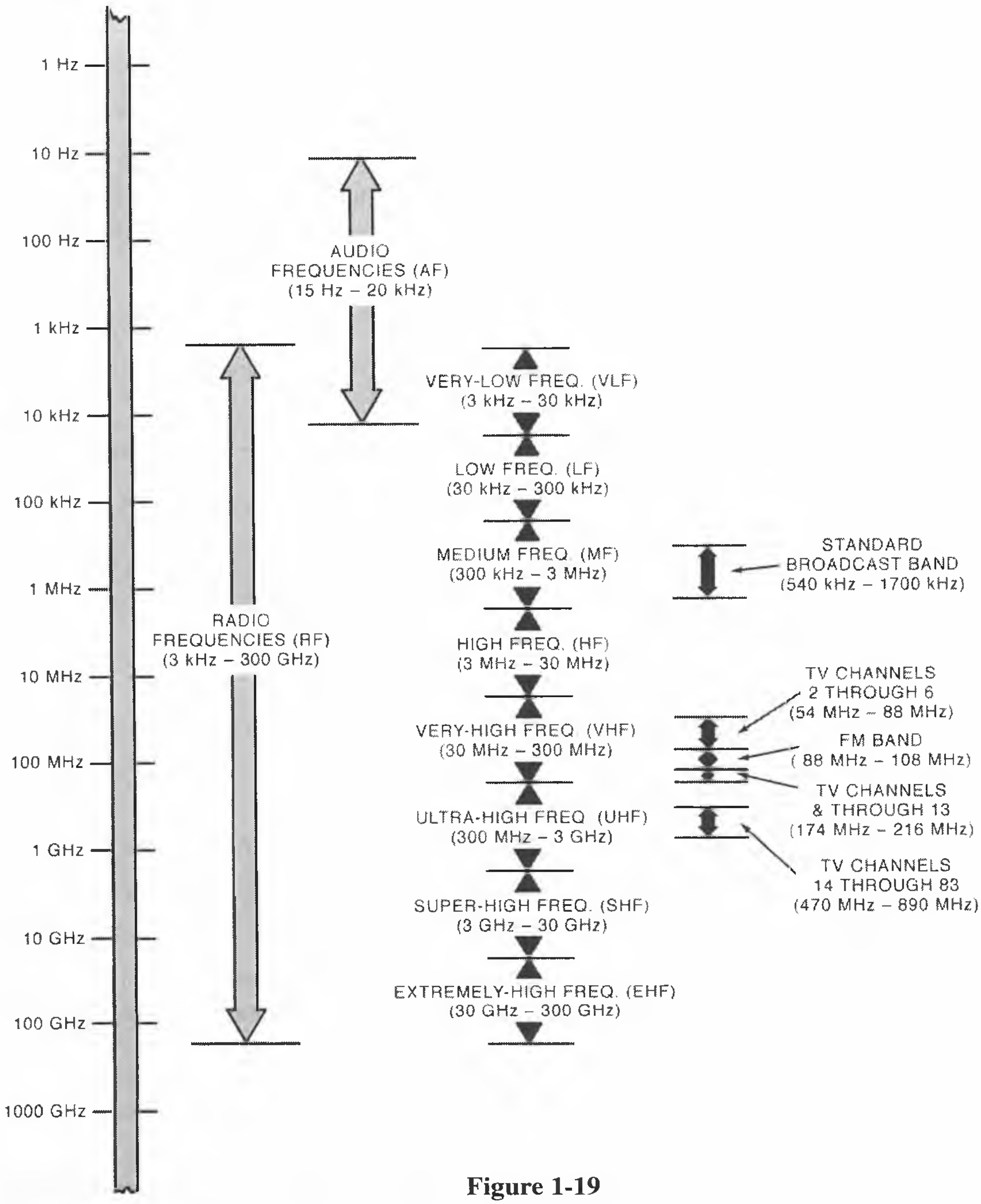


Figure 1-19
The frequencies used in electronic applications.

Programmed Review

48. The points on an AC waveform that have the greatest height or amplitude, are referred to as _________ values.

49. (peak) The highest points that occur on the positive and negative alternations of an AC sine wave are respectively referred to as the __________ peak value and the __________ peak value.

50. (positive, negative) The positive and negative peak values of a sine wave are equal. When you add together these positive and negative peak values, you obtain the _________-to-_________ value of the waveform.

51. (peak-to-peak) However, you can also determine the peak-to-peak value by multiplying the _________ value by 2.

52. (peak) Since a voltage or current sine wave remains at a peak value for only an instant during an alternation, the average value of the alternation is lower than its peak value. The average value of one alternation is equal to 0.636 times its peak value. This means that a voltage sine wave with a peak value of 25 volts has an average value of _________ volts.

53. (15.9) To determine the average value of one complete cycle of a sine wave, you add the average value of the positive alternation to the average value of the negative alternation. Since these values are equal but opposite in polarity, the average value of one cycle is _________ .

54. (zero) An alternating current that produces the same amount of heat in a given resistance as a direct current of 1 ampere, has an effective value of 1 ampere. The effective value of a voltage or current sine wave is equal to 0.707 times its peak value. This means that a current sine wave with a peak value of 3 amperes has an effective value of _________ amperes.

55. (2.12) Effective values are used more extensively than average values when you perform various AC calculations. Also, most voltmeters and ammeters are calibrated to read __________ values.

56. (effective) When an alternating current or voltage is specified but not specifically identified (such as 28 volts AC), the ___________ value is usually implied.

57. (effective) The amount of time that is required to generate one complete cycle of a sine wave is referred to as the period of the waveform. Therefore, if 2 cycles of a sine wave are produced in 10 seconds, the period of the sine wave is _________ seconds.

58. (5) The number of cycles that occur in a given period of time is called the frequency of the waveform. Frequency is expressed in terms of the number of cycles generated per second, but the term hertz (Hz) is used in place of the term cycles-per-second. Therefore a generator which produces 10 cycles of AC voltage per second operates at a frequency of 10 __________.

59. (hertz) The relationship between the frequency (f) and the period (T) of a waveform is expressed in the following equation:

$$f = \frac{1}{T}$$

If T is expressed in seconds, the value of f is in hertz. Therefore, if T equals 0.001 seconds, f must be equal to ___________ hertz.

60. (1000) When you transpose the previous equation, you find that T equals 1/f. Therefore if f equals 500 hertz, T must be equal to _________ seconds.

61. (0.002) A wide range of frequencies is used in electronic applications. In general, those frequencies are classified as either audio frequencies (AF) or __________ frequencies (RF).

62. (radio)

NONSINUSOIDAL WAVEFORMS

Although the sine wave is the most basic and widely used AC waveform, it is not the only type of waveform that is used in electronics. In fact, many different types of AC waveforms are used which may have very simple or extremely complex shapes.

You will now briefly examine some of the more common AC waveforms that are used in electronic equipment, for a variety of applications. These nonsinusoidal AC waveforms cannot be produced by the mechanically operated AC generators previously discussed. Nonsinusoidal waveforms are generated by electronic circuits that use a variety of semiconductor devices such as diodes and transistors. The actual semiconductor devices will be explained later in your studies of electronics. They were mentioned only to provide you with a prospective of how AC waveforms are used in the field of electronics. In this section, you are concerned with the actual types of waveforms, and how they relate to the sine wave.

The Square Wave

Figure 1-20 shows four different types of nonsinusoidal waveforms which represent either current or voltage. In each case, only one cycle of the waveform is shown. The waveform shown in Figure 1-20A is commonly referred to as a square wave because its positive and negative alternations are square in shape. The square shape of each alternation indicates that the voltage, or current, immediately increases to its maximum or peak value, at one polarity and remains there throughout that alternation. Then the voltage waveform immediately changes its polarity, or the current waveform reverses its direction. Note that the waveform jumps to a peak value almost instantly, and remains there for the duration of the second alternation. When a continuous train of these square waves is produced, the voltage or current simply continues to fluctuate back and forth between its peak values.

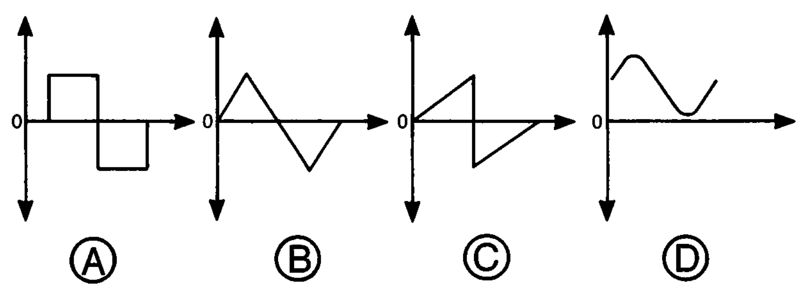


Figure 1-20
Nonsinusoidal waveforms.

Not all square waves are symmetrical, as shown in Figure 1-20A. In some cases, the positive half may be wider or narrower (longer or shorter time duration) than the negative half. Also, some square waves may have a positive peak value that is higher or lower (amplitude variations), than its negative peak value.

Although electrical power can be generated as square waves, square waves are more useful as an electronic signal. Square waves are used to represent electronic data because you can easily vary its characteristics.

The Triangular Wave

The waveform shown in Figure 1-20B is called a triangular wave because its positive and negative alternations are triangular in shape. Note that during the positive alternation the waveform rises at a linear rate from zero to a peak value and then decreases linearly back to zero. Then, on the negative alternation its polarity, or direction, reverses.

Triangular waves may have peak values that are higher or lower than those shown in Figure 1-20B. In other words, the positive and negative alternations may not always form a perfect triangle which has three equal sides. Triangular waves are used as electronic signals and are seldom used to provide electrical power.

The Sawtooth Wave

The waveform shown in Figure 1-20C is called a sawtooth wave. Sawtooth waves are similar to the triangular waves, but there are important differences. Sawtooth waves are formed when a voltage or current increases from zero to its positive peak value at a linear rate, then rapidly changes to its negative peak value, and then decreases back to zero at a linear rate. This sequence of events represents one complete cycle of the waveform. When a number of cycles are graphically plotted, the waveform has a sawtooth appearance. A sawtooth waveform has a shape that has some of the characteristics of both the square wave and the triangle waveform.

Sawtooth waveforms may vary slightly from the shape shown in Figure 1-20C. For example, the change from the positive peak value to the negative peak value may not occur almost instantaneously as shown. The change may require a small, but discernible, amount of time. Thus, the waveform appears to more closely resemble a triangular waveform than a square wave.

Fluctuating DC Waves

There are many instances when an electronic signal does not change direction. Instead, the signal varies or fluctuates at a specific rate. These waveforms cannot be truly defined as AC waveforms, but they still behave as if they were signals. For example, the waveform in Figure 1-20D actually represents a DC voltage or current which fluctuates in value in the same manner as a sine wave. The DC voltage fluctuates or rides above the horizontal line which serves as a time base and a zero reference line. This fluctuating DC waveform can produce the same effect as an AC sine wave in certain applications. Such a waveform might appear at an intermediate point within an electronic circuit, but it may be converted into a true AC signal before it reaches the output of the circuit.

The waveforms shown in Figure 1-20A, B, and C might also appear as fluctuating DC voltages within the circuits that generate them, and then converted to AC. In many applications, either an AC or a fluctuating DC signal can be used to perform a specific function. This is true, when the manner in which they change is more important than their specific voltage or current values.

The function generator shown in Figure 1-21 produces AC sine waves, square waves, and triangular waves over a frequency range of 0.1 hertz to 1 megahertz. The waveforms produced by this instrument are used to test the operation and calibration of electronic circuits and electronic equipment.

Figure 1-21
A typical function generator.

Programmed Review

63. Various types of nonsinusoidal AC waveforms are used in electronic applications. These waveforms are produced by electronic circuits, not by AC ___________ .
64. (generators) One type of AC waveform has positive and negative alternations which are square in shape and is therefore called a ___________ wave.
65. (square) When the positive and negative alternations have the shape of a triangle, the waveform is called a ___________ wave.
66. (triangular) Another waveform which increases in value at a linear rate and then suddenly jumps from its positive peak value to its negative peak value and then decreases to zero at a linear rate, is called a ___________ wave.
67. (sawtooth) A waveform which varies in value, but not in polarity or direction, is referred to as a ____________ DC waveform.
68. (fluctuating) Fluctuating DC waveforms behave as if they were _________ waveforms, and in many cases can perform the same basic functions.
69. (AC) Although an electronic circuit may produce an output AC waveform, at various points within the circuit the waveform may actually be a ____________ DC waveform.
70. (fluctuating)

SUMMARY

Unlike direct current (DC), which flows in only one direction and has a steady value, an alternating current (AC) flows in one direction and then the other. Furthermore, the value or magnitude of an alternating current usually varies as it flows in each direction.

Alternating current is used more extensively than direct current because it is more versatile. Alternating current may be used as a source of electrical power or energy, or it can be used to carry information or intelligence and thus serve as an electronic signal.

The electrical power that is produced for homes is actually alternating current. This AC power is produced by large AC generators at the power plant and distributed through a network of transmission lines to various homes and industries.

Alternating current is used instead of direct current in applications where large amounts of electrical power are required because it is easier and cheaper to produce. Furthermore an AC voltage can be converted to a higher or lower voltage very easily. AC may also be easily converted into DC.

An alternating current may be used as an electronic signal to carry information from one point to another because you can vary its characteristics in a desired manner. The AC signal may be carried by wires or transmission lines, or it may be converted to electromagnetic waves which can be transmitted through space.

An AC generator is able to produce an alternating current because it uses a process known as electromagnetic induction. Electromagnetic induction is simply a process which induces a voltage into a conductor. The induced voltage appears when the conductor moves through a magnetic field.

The voltage that is induced within a conductor is affected by the strength of the magnetic field, the speed of conductor movement, the length of the conductor in the field, and angle at which the conductor cuts the field. When you consider all of these factors, you can form one simple rule which states that the voltage induced into a conductor is directly proportional to the rate at which the conductor cuts the magnetic field.

The direction of conductor motion and the direction of the magnetic field determine the polarity of the induced voltage.

You can form a simple AC generator by bending a wire into a loop (called an armature) and rotating the armature within a magnetic field. Slip rings and brushes allow you to extract the AC voltage that is induced into the armature.

The AC output voltage that is produced by an AC generator varies from zero to maximum and back to zero again as the armature completes one-half of a revolution. Then, during the next one-half revolution, the voltage varies in the same manner but its polarity is opposite. One complete revolution of the armature produces an AC voltage that changes in value and polarity. If you connect a load resistance to the generator, the AC output voltage causes a corresponding AC current to flow through the load.

When you graphically plot the output voltage values with respect to armature position or time, you form a curve which shows how the AC voltage varies. Such a curve is called a waveform.

The AC voltage that is produced by the simple generator varies from zero to its maximum value according to the sine function, and then decreases to zero in the exact opposite manner. The AC voltage changes in this manner in each direction. For this reason, the AC voltage varies in a sinusoidal manner. When you graphically plot this AC waveform, it is called a sinusoidal waveform or simply a sine wave.

One complete revolution of the armature produces one cycle of output voltage. One cycle is further divided into two alternations. One alternation is called the positive alternation and corresponds to the first one-half revolution of the armature. The other alternation is called the negative alternation and corresponds to the second one-half revolution of the armature.

The maximum value that is reached during each alternation is called a peak value. The total value of a waveform, between its peak values, is called its peak-to-peak value.

The average value of one alternation is equal to 0.636 times the peak value. However, the average value of one complete cycle is zero.

The effective value of an AC sine wave is equal to 0.707 times its peak value. A current sine wave with an effective value of 1 ampere produces the same amount of heat in a given resistance as a direct current of 1 ampere. The effective value is also called the root-mean-square or rms value.

The period of a sine wave is the time required to produce one complete cycle. The number of cycles that occur in a specified period of time is called the frequency. The period is usually measured in seconds and the frequency is measured in hertz (cycles per second).

A variety of nonsinusoidal waveforms are also used in electronic applications. These waveforms are usually named for their shape. Such waveforms include the square wave, triangular wave, and sawtooth wave.

UNIT EXAMINATION

The following multiple choice examination is designed to test your understanding of the material presented in this unit. Place a check beside the multiple choice answer (A, B, C, or D) that you feel is most correct. After you complete the examination, compare your answers to the correct ones that appear in the Examination Answer Sheet which follows.

1. Alternating current changes in:

   A. direction only.
   B. value only.
   C. both value and direction.
   D. frequency and value but not direction.

2. Alternating current is used as:

   A. a source of electrical power and as a means of carrying information or intelligence.
   B. a source of power only.
   C. a means of carrying information only.
   D. an AC signal only.

3. A device which utilizes electromagnetic induction to producing an AC voltage is called:

   A. an oscillator.
   B. an induction motor.
   C. a battery.
   D. an AC generator.

4. In order for electromagnetic induction to occur, a conductor must:

   A. be held stationary in a magnetic field.
   B. cut across magnetic lines of force.
   C. move parallel with the lines of force.
   D. move so that no lines of force touch its surface.

5. The essential elements which are needed to form a basic AC generator are:

   A. slip-rings, brushes, and a magnetic field.
   B. an armature, slip-rings, and brushes.
   C. slip-rings and brushes.
   D. an armature, slip-rings, brushes, and a magnetic field.

6. When you graphically represent the AC voltage that is produced by an AC generator, you will produce a pattern or waveform which is commonly referred to as a:

   A. sawtooth wave.
   B. triangular wave.
   C. sine wave.
   D. square wave.

7. One cycle of an AC sine wave contains:

   A. two positive alternations and one negative alternation.
   B. two negative alternations.
   C. only one alternation.
   D. one positive alternation and one negative alternation.

8. The maximum value which occurs during an alternation of a sine wave is called the:

   A. peak point.
   B. peak value.
   C. peak-to-peak value.
   D. positive peak-to-peak value.

9. A voltage sine wave with a peak value of 200 volts has an average value of:

   A. 314.5 volts.
   B. 282.8 volts.
   C. 127.2 volts.
   D. 141.4 volts.

10. A current sine wave with a peak value of 16 amperes has an effective value of:

    A. 10.18 amperes.
    B. 11.3 amperes.
    C. 22.63 amperes.
    D. 25.16 amperes.

11. A voltage sine wave that has an effective value of 300 volts has a peak-to-peak value of:

    A. 471.7 volts.
    B. 943.4 volts.
    C. 424.2 volts.
    D. 848.4 volts.

12. If 20 cycles of a sine wave are generated in 100 seconds, the sine wave has a period of:

    A. 5 seconds.
    B. 10 seconds.
    C. 20 seconds.
    D. 1 second.

13. A sine wave with a period of 0.0125 seconds has a frequency of:

    A. 20 hertz.
    B. 160 hertz.
    C. 40 hertz.
    D. 80 hertz.

14. The AC waveform that is most widely used is the:

    A. square wave.
    B. triangular wave.
    C. sawtooth wave.
    D. sine wave.

15. Most AC voltmeters and ammeters are calibrated to measure:

    A. rms values.
    B. average values.
    C. peak values.
    D. peak-to-peak values.

EXAMINATION ANSWERS

1. C — Alternating current varies from zero to a maximum value and back to zero in one direction, and then varies in the same manner in the opposite direction.

2. A — Large amounts of AC power are easy to produce, and AC can be used to carry information, and therefore serve as an electronic signal.

3. D — AC generators may be very small or extremely large and can be used to generate relatively low or very high AC voltages and currents.

4. B — There must be relative motion between a conductor and a magnetic field and the conductor must actually cut across the lines of force.

5. D — An armature must be rotated within the magnetic field and the voltage that is induced into the armature is extracted with slip-rings and brushes.

6. C — The AC voltage varies according to the sine function which produces a sinusoidal waveform or sine wave.

7. D — The two halves of a cycle are identified as the positive and negative alternations.

8. B — One cycle of a sine wave has two alternations and two peak values which are referred to as the positive peak value and the negative peak value.

9. C — The average value is equal to 0.636 times the peak value or $0.636 \times 200 = 127.2$ volts.

10. B — The effective value is equal to 0.707 times the peak value or 0.707 ×× 16 = 11.3 amperes.

11. D — The peak value of the sine wave is equal to 1.414×300 or 424.2 volts. Therefore, the peak-to-peak value would be equal to 2×424.2 or 848.4 volts.

12. A — The period is the time required to produce one cycle. Therefore, the period is equal to 100/20 or 5 seconds. In other words, it takes 5 seconds to generate each cycle.

13. D — Frequency is the number of cycles generated per second. The frequency in hertz (1 hertz equals 1 cycle per second) is equal to 1 divided by the period (which is measured in seconds). The frequency, therefore, is equal to 1/0.0125 or 80 hertz.

14. D — The sine wave is the most basic and widely used waveform.

15. A — Most AC voltmeters and ammeters measure rms or effective values.

UNIT 2

AC MEASUREMENTS

CONTENTS

INTRODUCTION

If you plan to operate, repair, or design electronic equipment, you must understand how to use electronic test instruments, and to some extent how they were created. By this time, you are already familiar with the operation of DC voltmeters, ammeters, and ohmmeters. However, there are a number of test instruments that are designed specifically for AC measurements.

In this unit, you will study a variety of test equipment. You will learn how the equipment operates and how to use it. Since it is necessary that you understand current and voltage relationships in AC electronics, you will also examine these relationships in AC resistive circuits. In addition, you will perform experiments that are designed to demonstrate what you have learned.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define Lissajous pattern, CRT, graticule, and in-phase.
2. Explain the operation of the basic rectifier-type, moving-coil meter.
3. State how to increase either the current or voltage range of a meter movement.
4. Explain the operation of a thermocouple meter.
5. State the proper way to use a clamp-on meter and its principles of operation.
6. Explain the operating principles of a wattmeter and state how and why it is used.
7. Explain the advantages of an oscilloscope when compared to an AC voltmeter.
8. Explain how the oscilloscope is used to measure a waveform's pulse width, period, amplitude, rate of change, and phase relationships.
9. Analyze both series and parallel resistive AC circuits and determine their current and voltage values.
10. State the phase relationship between current and voltage in a resistive circuit.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "AC Meters."	______
☐ Complete Programmed Review Frames 1-23.	______
☐ Read "Oscilloscopes."	______
☐ Complete Review Frames 24-37.	______
☐ Read "Resistance in AC Circuits."	______
☐ Complete Programmed Review Frames 38-49.	______
☐ Perform Experiment 1.	______
☐ Perform Experiment 2.	______
☐ Study the "Summary."	______
☐ Complete the Unit Examination.	______
☐ Check the Examination Answers.	______

AC METERS

A variety of AC meters are used to measure alternating current and voltage values. Most of these meters are electromechanical devices which depend upon induced magnetism for operation. You will now examine some of the most commonly used AC meters to see how they operate, and how you should use them.

Rectifier-Type, Moving-Coil Meters

One popular type of AC meter consists of a moving-coil meter movement in conjunction with a group of rectifier diodes. Actually, the meter movement is designed to measure direct current rather than alternating current. Diodes, or rectifiers, convert the incoming AC into DC so that it can be measured by the meter movement.

THE BASIC METER MOVEMENT

The moving-coil meter movement is also commonly referred to as a d'Arsonval meter movement in honor of its inventor, Arsene d'Arsonval. This meter movement is essentially the heart of the rectifier-type, moving coil meter.

A typical moving-coil meter movement is shown in Figure 2-1. A horseshoe magnet produces a stationary magnetic field which cuts across a moving coil as shown. The moving coil consists of many turns of fine wire on an aluminum frame and the coil is mounted so that it can rotate within the magnetic field much like the armature of a mechanical AC generator. However, the coil cannot rotate 360 degrees which is one complete revolution. Instead, the frame can only move between specific limits. This is because a pointer (indicator needle) is attached to one end of the coil so that it moves or swings as the coil rotates. This pointer is allowed to move only between the left and right retaining pins as shown. The moving coil also rotates around a soft iron core which is fixed in place. The iron core helps maintain a uniform magnetic field between the opposite poles of the magnet.

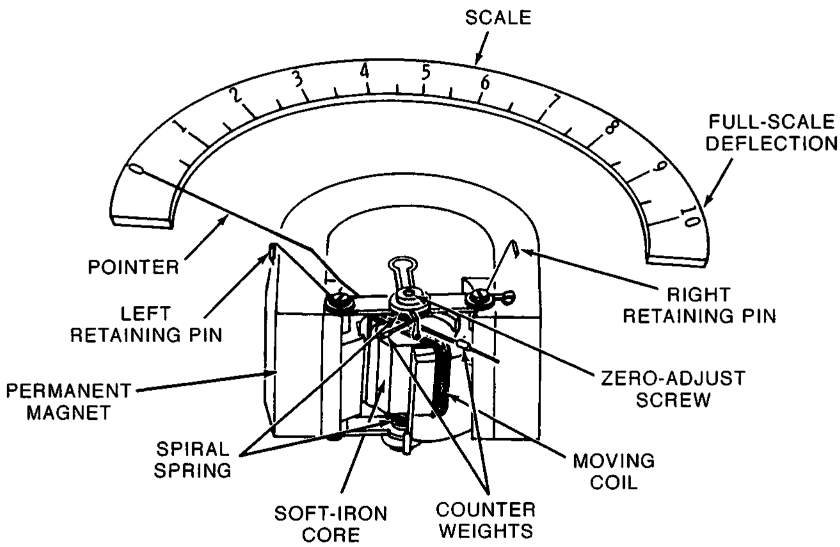


Figure 2-1
The moving-coil meter.

The spiral springs shown in Figure 2-1 force the coil and its associated pointer to the extreme left so that the pointer is near the left retaining pin. In this position, the pointer rests above the zero calibration mark on the meter's scale. The spiral springs also provide current paths to the moving coil. The two ends of the moving coil connect to the inner ends of the spiral springs. The outer end of the rear spring is fixed in place, but the outer end of the front spring connects to a zero adjust screw. This screw allows you to control the tension on the spring and mechanically reposition the pointer. Normally, you adjust this screw so that the pointer rests over the zero position. Counterweights are attached to the pointer so that it is perfectly balanced and rotates smoothly on its pivots.

The action that takes place in the moving-coil meter movement is illustrated in Figure 2-2. Figure 2-2A shows a front view of the basic meter movement. As shown, the moving coil rotates around the soft-iron core and remains within the magnetic field. This illustration also shows the relative position of the pole pieces which are attached to the opposite poles of the magnet. These pole pieces help maintain a uniform magnetic field through which the moving coil is to be rotated.

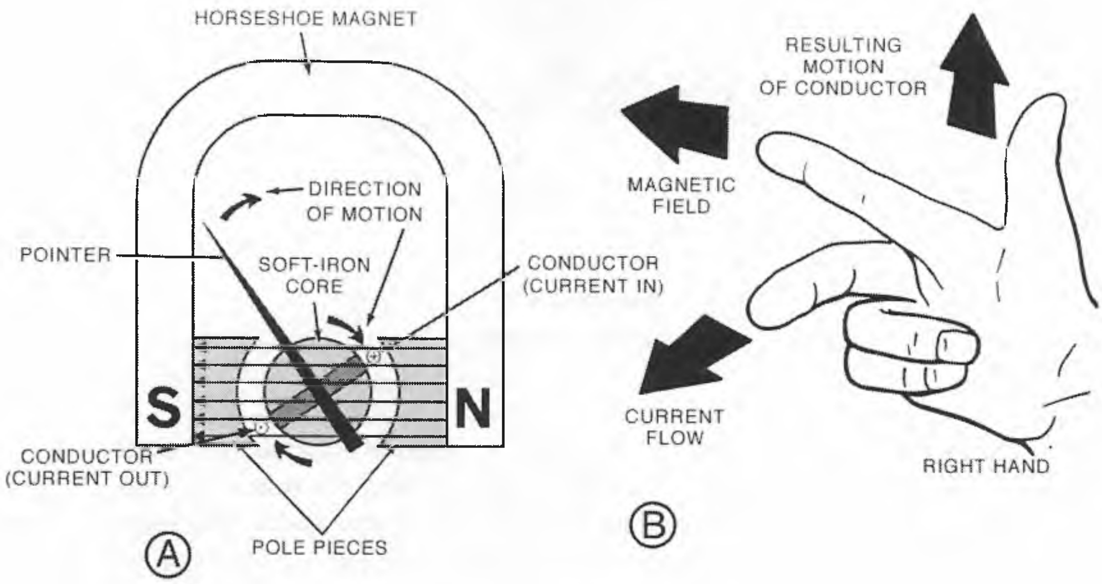


Figure 2-2
Motor action of moving coil.

The meter movement in Figure 2-2 has been simplified so that only one turn of the moving coil is shown. This single turn is viewed from one end, or in other words, shows a cross sectional view of the moving coil. When current is forced through the coil so that it flows into the upper right conductor, and out of the lower left conductor, a unique action occurs. The current through the conductor creates a magnetic field which surrounds the conductor and this field interferes with the stationary field produced by the magnet. The interaction of the fields causes the coil to move. This action is exactly opposite to the generator action that was described in Unit 1. In an AC generator, an armature moves through a magnetic field and a voltage (and corresponding current) is induced into the armature loop. However, in this case a current is forced through a loop of wire and the loop is forced to turn because the fields interact. Electrical energy is therefore converted to mechanical energy, instead of mechanical energy being converted to electrical energy.

In Unit 1 you defined a generator as a device that converts mechanical motion (energy) into electrical energy. The action described above converts electrical energy into mechanical motion. This is defined as motor action.

The moving-coil meter movement operates on the same basic principle as an electric motor. The moving-coil responds to current just like the armature in a motor. It is possible to analyze the exact manner in which the fields interact to determine the direction of conductor motion. However, you can use a simple rule to determine the same result. This rule is commonly referred to as the *right-hand motor rule* and is illustrated in Figure 2-2B. When you position your right hand as shown, your forefinger points in the direction of the magnetic field, your middle finger (which is bent out from the palm at 90 degrees) points in the direction of current flow, and your thumb points in the direction of conductor motion.

When you apply the right hand rule to the coil in Figure 2-2A, you find that the upper right side of the coil is forced down and the lower left side is forced up. Therefore, the pointer is forced to move up scale from left to right, or in a clockwise direction (CW). The coil must move against the tension provided by the spiral springs and the resulting pointer deflection is proportional to the amount of current flowing through the coil. The higher the current, the greater the deflection.

Like all meter movements, the moving-coil meter movement is rated according to the amount of current required to produce full scale deflection. For example, a 1-milliampere meter movement deflects full scale when 1 milliampere of current flows through it. Some meters are designed to be more sensitive than others. For example, a meter with a 200-microampere rating is more sensitive than a meter with a 1-milliampere rating. Other commonly used meters, which are even more sensitive, have ratings of 100 and 50 microamperes.

It is also important to note that all moving-coil meter movements are designed to operate with only direct current. These meters will not respond properly when you apply alternating current directly to them.

THE RECTIFIERS

You can use a moving-coil meter movement to measure alternating current if you convert the AC to DC before it is applied to the meter movement. You can accomplish this with a group of semiconductor devices called a diodes or rectifiers. A diode is a 2-element device that converts AC to pulsating DC (rectification process). These rectifier components are connected between the input AC and the meter and allow current to pass through the meter in one direction.

One of the earliest rectifier diodes used in conjunction with meter movements is illustrated in Figure 2-3A. It consists of a copper disk which has a layer of copper oxide on one side. A lead disk is placed against the copper oxide layer and the entire unit is compressed between two metal pressure plates. A bolt holds the pressure plates in place. This type of rectifier diode is commonly referred to as a *copper oxide rectifier.*

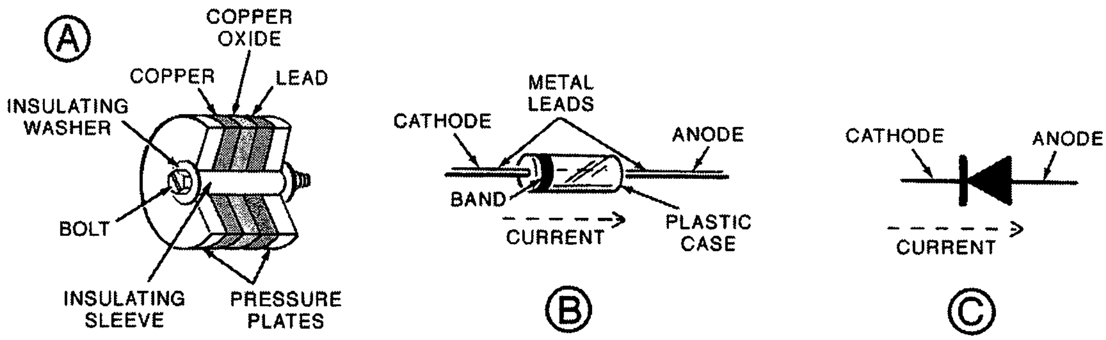


Figure 2-3
A typical copper oxide rectifier (A),
junction diode (B),
and rectifier symbol (C).

The copper oxide rectifier allows current to flow readily from the copper to the copper oxide, but allows only a small current to flow in the reverse direction. Therefore, it is essentially a unidirectional conductor of electrical current. An ideal rectifier acts as a short in one direction and an open in the opposite direction. However, you cannot achieve this ideal situation does not exist in practice and most practical rectifiers have substantially less that ideal characteristics.

The copper oxide rectifier has been replaced in most applications by a more efficient device known as a *junction diode rectifier* or simply a *junction diode.* A junction diode is made from a semiconductor material (a material which is not a good conductor or a good insulator) such as germanium or silicon. The semiconductor material is processed so that it takes on unidirectional characteristics. The semiconductor device is then mounted in a glass, metal, or plastic package which protects it from environmental hazards. A typical junction diode is shown in Figure 2-3B. The device shown has two metal leads which extend from opposite ends of a plastic case. These leads are internally connected to the opposite ends of the junction diode rectifier. Current can readily flow into one lead and out of the other lead in the direction shown, but only a small leakage current can flow in the opposite direction.

One end of the rectifier shown in Figure 2-3B is marked with a band. This end of the diode is referred to as the *cathode* and the opposite end is called the *anode*. Current always flows from the cathode end to the anode end as shown. Remember, current flows into the point of the arrow.

Figure 2-3C shows the schematic symbol that is commonly used to represent a rectifier. Note that the symbol consists of a bar and an arrow, and that current (electron) flow is always against the direction that the arrow is pointing. In other words, current can flow from the bar to the arrow but not in the opposite direction.

THE COMPLETE AC METER

The schematic diagram of a rectifier-type, moving-coil meter is shown in Figure 2-4A. Note that four rectifiers are used in conjunction with one meter movement. The four rectifiers are identified as D_1, D_2, D_3, and D_4 and are arranged in what is called a *bridge rectifier* configuration. The two input terminals of the circuit are identified as A and B.

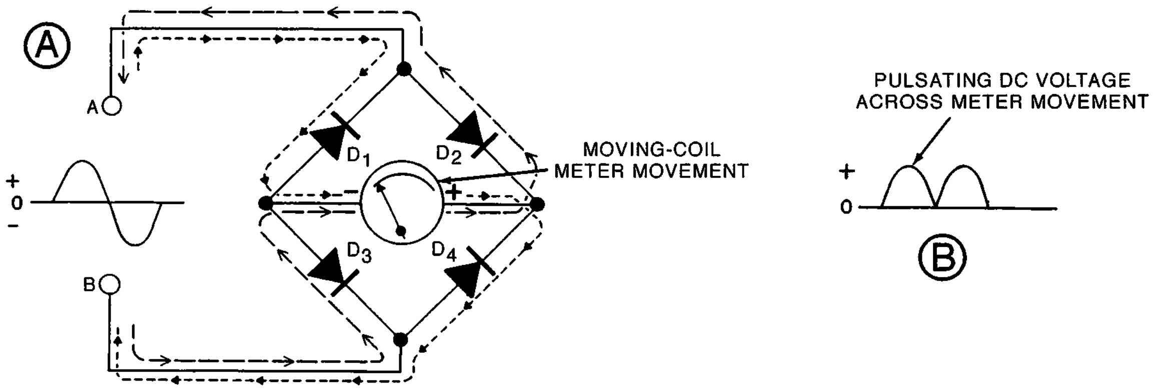


Figure 2-4
A rectifier-type, moving-coil meter.

Assume that an AC generator is connected to input terminals A and B, and that this generator supplies a continuous alternating current that varies in a sinusoidal manner. Also assume that during each positive alternation of the sine wave, terminal A is positive with respect to terminal B. During each positive alternation the circuit current flows along the path indicated by the long dashed lines. Current flows from terminal B, through D_3, the meter movement, D_2, and out terminal A. During each negative alternation, B is positive with respect to A and cur-

rent flows along the path indicated by the short dashed lines. In other words, current flows from terminal A, through D_1, the meter movement, D_4, and out terminal B. Note that even though the input current changes direction, the current through the meter movement is always in the same direction. The four rectifiers therefore convert the input AC into pulsating DC, as shown in Figure 2-4B.

The process of converting AC to DC is referred to as *rectification* and this is why the diodes used in this application are referred to as simply rectifiers. Furthermore, the rectifiers in this circuit convert both halves of the sine wave into a pulsating direct current and therefore provide *full-wave* rectification. Less complicated circuits, which use only one or two rectifiers, may also be used to provide *half-wave* rectification. In this last process, only one of the alternations is allowed to flow through the meter movement.

The current through the meter movement flows in pulses since each alternation rises from zero to a peak value and drops back to zero again. Unless the frequency of the AC input is extremely low, the meter movement is not able to follow the variations in the pulsating current. Instead, the meter's pointer responds to the average value of the AC sine wave. The average of an alternation is equal to 0.636 times the peak value. However, the scale on the meter is usually calibrated in effective or rms values. In other words, the numbers on the meter scale represent effective values which are equal to 0.707 times the peak value. The effective value of a sine wave is much more important than the average value since effective values are used in most calculations that involve current and voltage.

ELECTRICAL CHARACTERISTICS

A variety of rectifier-type, moving-coil meters are available which can measure a wide range of alternating currents. Each meter is designed to measure up to a certain maximum current. For example, some meters may have calibrated scales which extend from 0 to 1 milliampere, 0 to 10 milliamperes, or 0 to 100 milliamperes.

Most rectifier-type, moving-coil meters have an accuracy of ± 5%. This accuracy measurement is based upon the percentage of error in the meter reading at full-scale deflection. For example, a 100-milliampere meter which has an accuracy of ± 5% might be off by as much as ± 5 milliamperes when it indicates a current of 100 milliamperes. However, this same full-scale accuracy of ± 5% pertains to any other meter reading. For example, if the meter indicates 50 milliamperes, the true reading could still be off by as much as ± 5 milliamperes.

The rectifier-type, moving-coil meter uses a linear scale. This means that the numbers or values on the scale are equally spaced. Therefore, the pointer's deflection is always directly proportional to the current that flows through the meter movement. A typical scale for this type of meter is shown in Figure 2-5.

Figure 2-5
A typical linear scale.

The rectifier-type, moving-coil meter is useful when you need to measure alternating currents over a specific frequency range. This type of meter is usually quite accurate over a frequency range that extends from approximately 10 hertz to as much as 10,000 or 15,000 hertz. Below a lower limit of approximately 10 hertz, the meter's pointer tends to fluctuate in accordance with the changes in input current. Since the meter's pointer is never stationary, it is difficult to accurately read the meter. Above the upper frequency limit (10 kHz), the meter readings are usually too inaccurate to be usable. In fact, the accuracy of the meter progressively gets worse as frequency increases beyond a few hundred hertz because the rectifiers have a certain amount of internal *capacitance* and the moving-coil meter movement has a certain amount of internal *inductance*. These two internal properties present a certain amount of opposition to the flow of alternating current through the meter and this opposition varies with frequency.

Moving-Vane Meters

The meter described earlier requires rectifiers to convert the AC into DC, which is needed to operate the meter movement. However, some meter movements are capable of responding directly to an AC input. One of these types is the *moving-vane* meter or a *moving-iron* meter. This type of meter contains a movable iron vane, and depending upon the shape of the vane, it may be classified as either a *radial-vane* or a *concentric-vane* meter. You will now examine both of these basic types and then consider their important electrical characteristics.

THE RADIAL-VANE METER MOVEMENT

The basic radial-vane mechanism is shown in Figure 2-6. Note that it contains essentially the same basic components as the meter movements previously described. However, these components are arranged in basically the opposite manner. In other words, a coil is used in this meter movement, but the coil is stationary. It surrounds a moving iron vane which is attached to the meter's pointer as shown. A stationary iron vane is mounted inside the coil, parallel to the moving vane. When current flows through the coil (in either direction) it produces a magnetic field that surrounds the coil. This field passes through the moving and stationary vanes in the same direction and magnetizes both vanes in the same direction. Therefore, the vanes always have north and south poles which are directly adjacent to each other. Since a fundamental rule of magnetism states that like poles repel each other, the movable vane is pushed away from the stationary vane, and the meter's pointer is forced to rotate against the tension provided by the springs. Figure 2-6 shows the tops of the vanes to be north poles while the bottoms are south poles. This condition occurs only when current flows in one specific direction. When current flows in the opposite direction, the poles are interchanged. However, in either case, the two vanes are pushed apart.

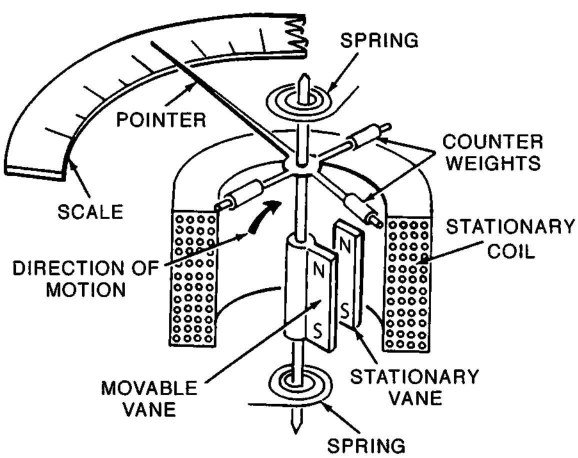


Figure 2-6
The radial-vane meter movement.

A higher current through the coil produces a stronger magnetic field around the coil. This results in greater induced magnetism within the vanes. The increased magnetism causes the pointer to deflect further. In other words, the higher the current, the greater the pointer deflection. As shown, the scale must be appropriately calibrated so that the pointer indicates the amount of current that is applied to the meter movement. Like most AC meters, the scale is usually calibrated in effective values. The scale extends from zero to the maximum value that the meter movement is designed to measure.

THE CONCENTRIC-VANE METER MOVEMENT

The basic concentric-vane meter movement is shown in Figure 2-7. Note that it is similar to the radial-vane movement, except that its stationary and moving iron vanes are semicircular in shape. The moving vane is mounted inside the stationary vane and it is attached to the pointer. The moving vane has square edges, but the stationary vane is tapered along one edge.

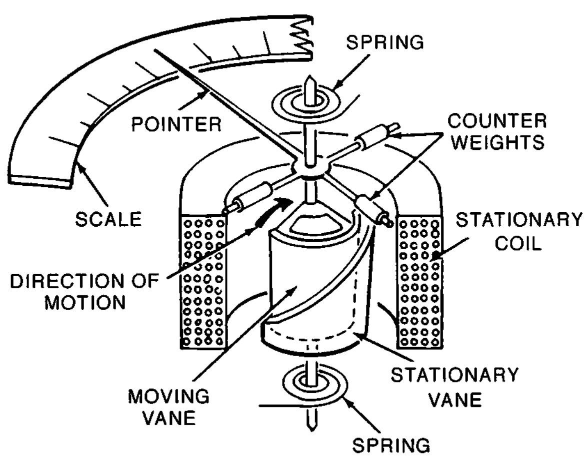


Figure 2-7
The concentric-vane meter movement.

When current flows through the coil, it produces a magnetic field around the coil. The magnetic field passes through both vanes which causes them to become magnetized in the same direction. However, the magnetic lines of force are not distributed uniformly through the stationary vane because of its tapered edge. Fewer lines of force pass through the narrow end than the wide end because the narrow end offers higher resistance or opposition to the magnetic lines of force. The wider end provides an easier path for the lines of force, which allows more lines of force to be produced. Therefore, the wider end of the vane is more strongly magnetized than the narrow end. The strongest repulsion occurs between the wide end of the stationary vane and the moving vane. Since the repulsion at the narrow end of the stationary vane is less, the movable vane is forced to rotate toward the tapered end of the stationary vane. This force is against the spring tension, provided by the springs, and causes the pointer to deflect up scale. The higher the current through the meter movement, the greater the pointer deflection.

ELECTRICAL CHARACTERISTICS

Although moving-vane meters are primarily used to measure AC, they may also be used to measure DC values if their scales have been appropriately calibrated. This is possible because the moving and stationary vanes always repel, regardless of which direction current flows.

In general, moving-vane meters require more current to produce full-scale deflection than the rectifier-type moving-coil meters. Therefore, moving-vane meters are seldom used in low-power circuits. They are more suited for measuring the relatively high currents in AC power circuits.

Most moving-vane meters have a full-scale accuracy of approximately ± 5%, but they cannot provide accurate readings over a wide range of frequencies. Most of these meters cannot provide accurate readings at frequencies that are much above 100 hertz and are used mostly in applications where 60-hertz AC power is involved.

The scale of a moving-vane meter is usually nonlinear. In other words, the values on the meter's scale are not equally spaced. In fact, these meters usually provide a pointer deflection that increases with the square of the change in current. For example, suppose that 10 milliamperes of current causes the pointer to deflect a distance of 1 inch on the meter's scale. When you increase the current to 20 milliamperes, or double it, the pointer does not deflect 2 inches (twice as far). Instead, the pointer deflects four times as far or 4 inches. Likewise, if you increase the current to 3 times its initial value, the pointer will deflect 9 times as far (9 is the square of 3). If the input current becomes 4 times as great, the pointer will deflect 16 times its initial distance. Any meter that is calibrated in this manner has what is called a *square-law scale.*

A typical scale for a moving-vane meter is shown in Figure 2-8. Note that the values near the zero end of the scale are more closely spaced. With this type of scale it is difficult to accurately measure current values that fall near the zero end.

Figure 2-8
A typical nonlinear scale.

Thermocouple Meters

Thermocouple meters are also commonly used to measure AC. This instrument uses a device known as a *thermocouple* to generate the current needed to drive the meter movement. You will now briefly examine this meter and consider its important electrical characteristics.

METER OPERATION

The thermocouple meter consists of a thermocouple and a moving-coil meter movement as shown in Figure 2-9. The thermocouple is two dissimilar metal strips or wires which are joined at one end. When this junction is heated, the two metals produce a difference of potential or voltage across their opposite ends. The thermocouple therefore converts heat into an electrical voltage.

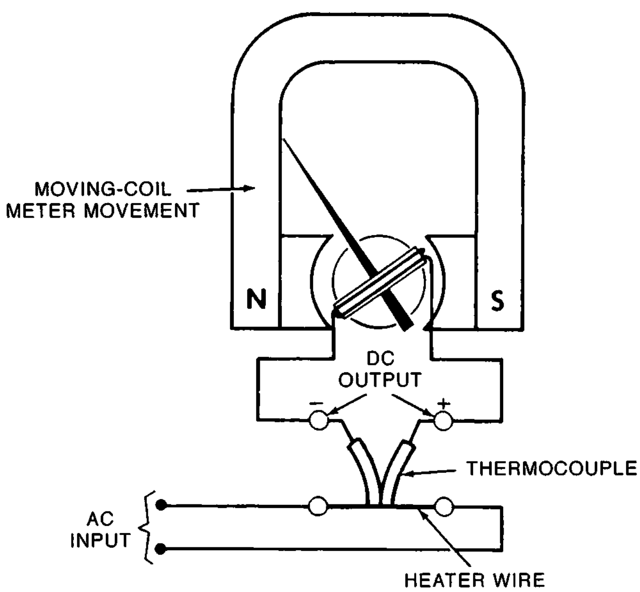


Figure 2-9
A basic thermocouple meter.

A short heater wire is placed against the thermocouple's junction as shown in Figure 2-9. The AC input is applied directly to the heater wire and this wire heats up to a temperature that is determined by the amount of current flowing through the wire. The heat produced by the wire causes the thermocouple to produce a DC output voltage which in turn causes current to flow through the moving-coil meter movement. This current causes the pointer to deflect and indicate the value of the input AC.

ELECTRICAL CHARACTERISTICS

A thermocouple meter can measure alternating currents over an extremely wide frequency range. In fact, its upper frequency limit extends well up into the radio frequency (RF) range. These meters are often used at frequencies as high as several gigahertz. However, they may also be used to measure DC if their scales have been appropriately calibrated. This is because thermocouple meters are completely insensitive to the rate at which the input current varies. They respond only to the amount of heat that is produced by the AC or DC input.

When a thermocouple meter is used to measure an alternating current that has an extremely high frequency, it is necessary to calibrate the instrument at that particular frequency. In other words, the meter should be calibrated to indicate the correct AC value at a particular frequency. This is because a phenomenon known as *skin effect* occurs at extremely high frequencies. Skin effect occurs because high frequency AC currents tend to flow near the outer surface of a wire. The higher the frequency, the higher the skin effect. This means that most of the conductor's interior is not used to support current and its resistance is higher than it normally is. Therefore, the effective resistance of the heater wire and the other wires within the meter vary with frequency which changes the internal resistance of the meter. This change in internal resistance affects the meter's response, and makes it necessary to calibrate the meter at the frequency that is to be measured.

When they have been properly calibrated, thermocouple meters provide quite accurate AC measurements. Typical meters usually have a full-scale accuracy of ± 2% or ± 3%, and certain types of laboratory instruments may have an accuracy of ± 1%. Furthermore, the thermocouple meter provides a pointer deflection which varies as the square of the change in AC input current and is just like the moving-vane meter that was previously described. Therefore, the thermocouple meter must also have a square law scale.

Clamp-on Meters

All of the meters described so far must be connected directly into an electronic circuit to measure current. However, there is one type of measuring instrument which does not have to be physically connected into the circuit in order to provide a current measurement. This device can be simply clamped over a conductor and it will indicate the amount of current flowing through the conductor. These clamp-on type meters are also referred to as *split-core* meters, *hook-on* meters, or *snap-around* meters. You will now briefly examine one of these meters and consider its important electrical characteristics.

METER OPERATION

A clamp-on meter basically consists of a transformer and a rectifier-type moving-coil meter, as shown in Figure 2-10. Transformer action is based upon a phenomenon called *electromagnetic mutual inductance*. This principle is explained in Unit 6. For now, you only need to know that as a current moves through a conductor, electromagnetic lines of flux (a magnetic field) is formed about the conductor. Its strength varies in direct proportion to the amount of current, and its polarization is dependent upon the direction of current flow. When an AC current reverses direction, the field collapses and then builds in strength with the opposite polarization. This build-up and collapse causes the fluctuating lines of force, that make up the magnetic field, to cut the secondary, and thereby induces an electromotive force (EMF), or voltage, into the secondary winding. This secondary voltage is rectified and ultimately used to cause the meter to deflect. These hand-held instruments are usually mounted within a small plastic case.

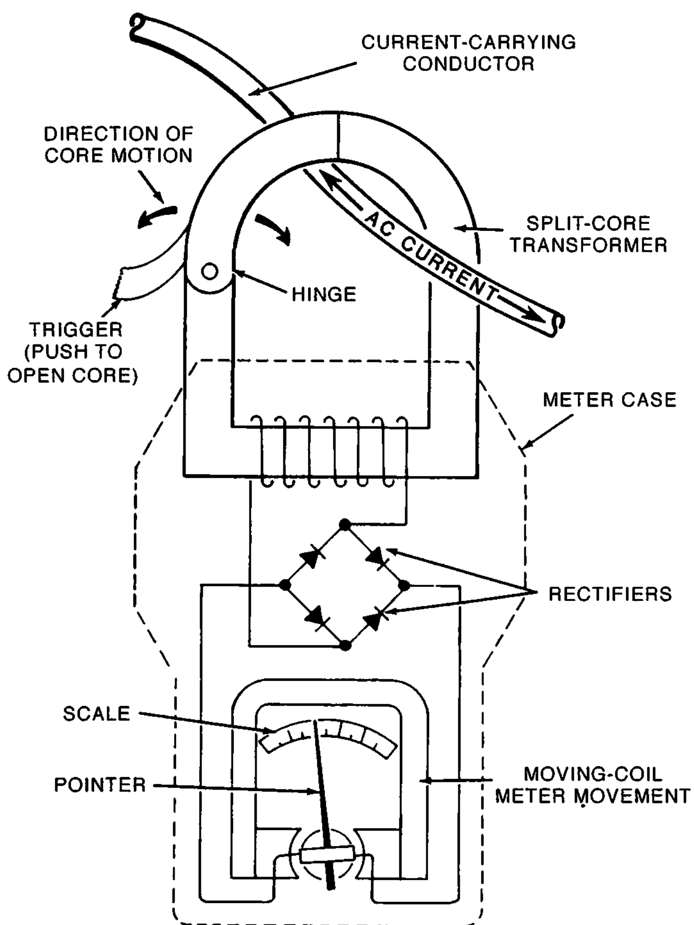


Figure 2-10
A basic clamp-on meter.

This meter utilizes a split-core transformer. One side of the transformer core is hinged and is movable. You press an attached trigger to open this section of the core. To measure the AC current in a conductor, you open the core (which is made of soft iron) and insert the conductor inside the core. You then close the core, as shown, so that it completely surrounds the conductor. It is important to make sure that the core is completely enclosed and that no air gap is present.

The AC current flowing in the conductor produces a circular magnetic field around the conductor. The strength of this field is proportional to the current that flows through the conductor. This magnetic field expands and collapses as the AC increases and decreases in value (amplitude). The field polarity reverses as the current changes direction. The iron core offers little opposition to the magnetic field (much less than air). This means that most of the lines of force pass through the core. However, in order for this to happen, the magnetic lines of force must cut across the coil that is wound around the opposite side of the core. When this happens, a voltage is induced into the coil which in turn causes an induced current to flow through the coil. The conductor, the core, and the coil, form a *transformer* with the conductor acting as the input or *primary* winding (which has only one turn) and the coil acting as the output or *secondary* winding.

The current that is induced into the secondary is an alternating current just like the current in the conductor. This AC is applied to the rectifiers which convert it to DC. The DC is then used to operate the moving-coil meter movement which causes its pointer to deflect. The meter is calibrated so that it indicates the effective value of the AC current that flows through the conductor.

ELECTRICAL CHARACTERISTICS

Since the clamp-on meter depends upon transformer action for operation, it can be used to only measure AC. The moving magnetic field that is produced by AC in the conductor is necessary to induce a voltage into the secondary coil of the transformer. The magnetic field that is produced by a direct current is constant, and therefore cannot pass through the transformer.

In general, the clamp-on meter is useful for measuring only relatively high alternating currents. This is because the current in the conductor must be high in order to produce a magnetic field that is strong enough to induce a significant amount of current into the secondary coil. These meters are often used to measure currents as high as several hundred amperes. They are usually used by electricians for power line checks rather than by electronic technicians.

Using AC Meters

Now that you have examined some of the basic types of AC meters, it is time to consider how these meters are used in typical applications. Although there are no complicated rules governing their use, there are some important points which you must consider. The basic AC meter is essentially a current-measuring device. It is also used to measure voltage and power. You will now see how these instruments are used to measure various quantities and the important precautions that you must observe when you use them.

MEASURING CURRENT

With the exception of the clamp-on meter, to measure current you insert the ammeter into the circuit in series with the component whose current is to be measured. In the case of DC currents, you must observe the proper polarity. When you use an AC current meter, the meter only responds to one of the alternations and polarity is not a problem.

AC meters are current-measuring instruments. They are available for measuring alternating currents over a variety of ranges. In general, any meter which is used to measure current, either AC or DC, is referred to as an *ammeter*. However, the terms *microammeter* and *milliammeter* specifically identify meters that measure currents in the microampere and milliampere ranges.

Many AC ammeters are designed to measure current over one specific range. For example, a meter may be calibrated to measure currents from 0 to 50 milliamperes, while another meter may have a scale which extends from 0 to 100 milliamperes. You could use these two meters to measure currents as high as 50 and 100 milliamperes respectively. If you exceed these values by a substantial margin, even momentarily, sensitive meter movements could become damaged.

The amount of current that is required to deflect the meter's pointer to its full-scale position is called the *meter sensitivity*. The two meters in the previous paragraph have meter sensitivities of 50 and 100 milliamperes respectively. Do not confuse meter sensitivity and meter movement sensitivity. Meter sensitivity is the maximum current that the meter can measure on any given scale. Meter movement sensitivity is the maximum current that can pass directly through the meter movement. Meter movement sensitivity is fixed at the time of manufacture and is usually printed on the face of the meter movement.

Certain types of ammeters are designed to have more than one current range. Such meters are usually equipped with a range switch which effectively changes the sensitivity of the meter and its operating range. A typical multirange ammeter circuit is shown in Figure 2-11A. Note that the instrument uses a 1 mA (1 milliampere) AC meter movement, three resistors, and a range switch. When the range switch is in the 1 mA position, only the meter movement is connected to the input terminals which gives the instrument a current range that extends from 0 to 1 milliampere.

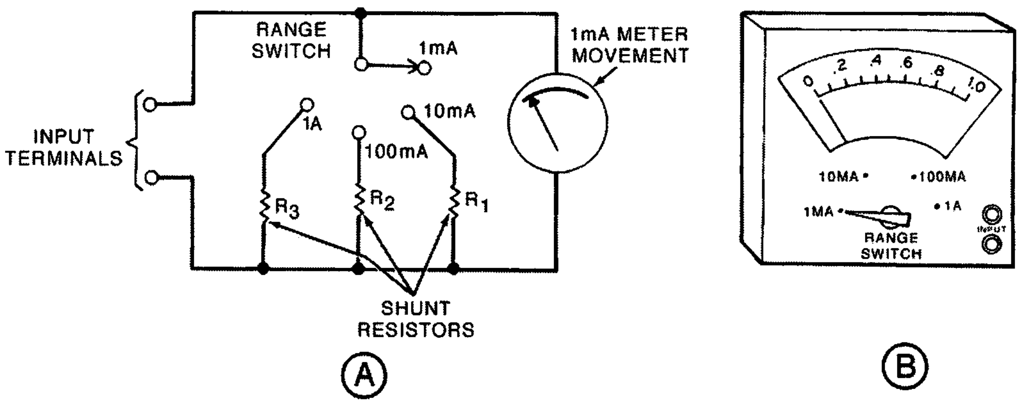


Figure 2-11
A typical multirange ammeter.

When the range switch is in the 10 mA position, resistor, R_1 is connected in parallel with the meter movement. When the switch is in this position, it can measure currents up to 10 milliamperes, even though the meter movement itself can only handle 1 milliampere of current. R_1 shunts the additional 9 milliamperes of current around the meter movement. In other words, when 10 milliamperes of current flow through the instrument, R_1 must carry 9 milliamperes of current so that only 1 milliampere flows through the meter movement.

When the range switch is in the 100 mA position, the instrument can measure up to 100 milliamperes of current because resistor R_2 shunts up to 99 milliamperes of current around the meter movement. When the range is set to the 1 A position, the instrument can measure up to 1 ampere (1000 milliamperes) of current since resistor R_3 shunts up to 999 milliamperes of current around the meter movement. Resistors R_1, R_2, and R_3 are appropriately referred to as *shunt resistors.*

The complete AC meter is shown in Figure 2-11B. Note that it uses only one scale which is calibrated from 0 to 1. This same scale is used on each range, therefore you must mentally adjust the decimal point on the scale to correspond to the range you are using. Some meters have more than one scale which allows you to read each scale directly.

When you use an ammeter to measure current, be sure that the current that you are measuring is not beyond the range of your ammeter. Always play it safe and start with the highest possible range if you are in doubt. Then work down to range that provides you with a measurable indication. Be sure that your meter is properly calibrated, and always check the pointer to make sure that it is on zero before you insert the meter into the circuit. If it is not, readjust the meter for a zero reading. Most meter movements have a mechanical zero adjustment that allows you to reposition the pointer.

When you use any type of ammeter, except the clamp-on type, to measure AC current, always connect the meter in series with the current to be measured. This means that it is necessary to break the circuit under test so that you can insert the ammeter. For example, if you wish to measure the current flow through a resistor, you must break the circuit on one side of the resistor and insert the ammeter as shown in Figure 2-12A. When you connect the ammeter in series, it again forms a complete circuit, and the current flows through the meter. When you measure the current through a component that is connected in series or parallel with other components, you must exercise extreme caution to be sure that the ammeter is in series with the correct component. For example, if you wish to measure the current through R_2 in Figure 2-12B, you must be sure that the meter is in series with R_2. When you break the circuit is broken and insert the meter at points A or C, you will measure the total current flowing through R_1. When the ammeter is inserted at point B, it measures the current through R_3.

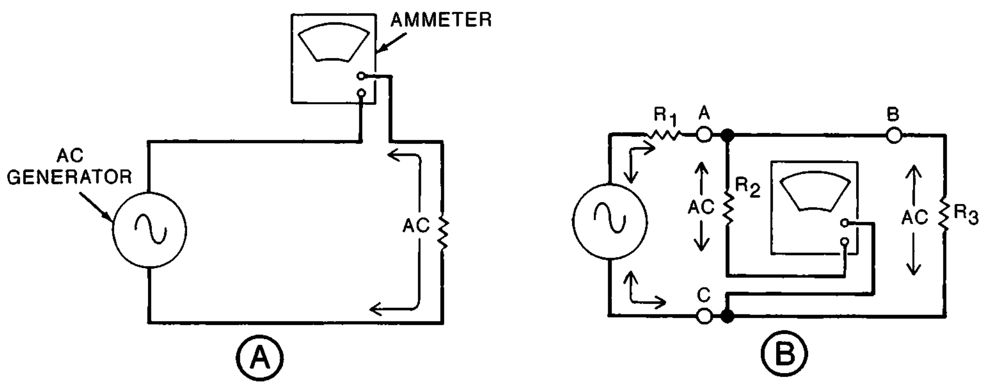


Figure 2-12
Measuring current with an ammeter.

Since the alternating current periodically changes its direction, it makes no difference which direction the meter is connected. In other words, the wires connected to the meter's input terminals (shown in Figure 2-12) could be interchanged and the meter would still function properly. You only need to make sure that you connect the meter in series with the alternating current. In this respect, AC meters are much easier to use than DC meters. DC meters must be connected so that the current flows through them in the proper direction. In other words, you must observe proper polarity.

MEASURING VOLTAGE

Although AC meters are current-measuring instruments, they can also indicate voltage. When they are used in this manner, additional components are required to limit the current that flows through the meter to the proper value. Instruments that are used to measure voltage, either AC or DC, are referred to as *voltmeters.*

Some voltmeters are designed to measure one specific range of voltages that extend from zero to some maximum value. However, many voltmeters are capable of measuring voltages over several ranges. These multirange meters are more versatile and are therefore more practical in applications where you need to measure a wide range of voltage values.

A typical multirange voltmeter circuit is shown in Figure 2-13A. Note that the instrument uses a meter movement, three resistors, and a range switch. When the range switch is set to the 1 V position, the instrument is capable of measuring AC voltages from 0 to 1 volt. When the range switch is in this position resistor R_1 is connected in series with the meter movement. This resistor has a resistance value that limits the current flow through the meter movement to its full-scale value when the AC voltage across the input terminals has an effective (rms) value of 1 volt. You must also take the internal resistance of the meter movement (although it is usually very low) into consideration when you determine this resistor value. This is necessary in order to ensure that the total resistance of the meter circuit has the proper value.

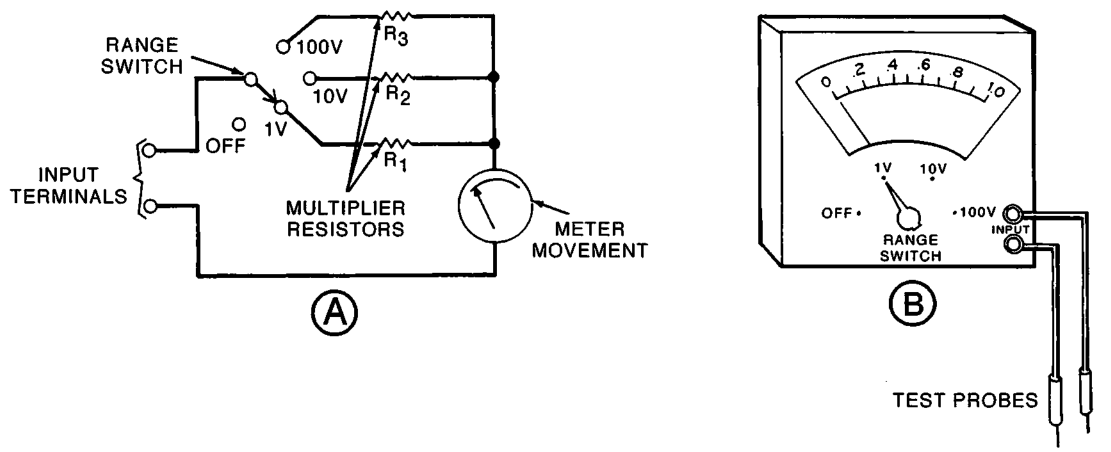


Figure 2-13
A typical multirange voltmeter.

When the range switch is set up to the 10 V position, the meter can measure effective voltages up to 10 volts. In this case, resistor R_2 is in series with the meter movement. This resistor has a higher value than R_1, and it limits the current through the meter movement to its full-scale value when the input voltage is

10 volts. When the range switch is set to the 100 V position, R_3 is switched into the circuit. This resistor is larger than R_2, and it limits the current through the meter movement to its full-scale value when the input value is 100 volts. Resistors R_1, R_2, and R_3 effectively multiply or extend the meter's voltage range by a factor of 10 in each case. These resistors are commonly referred to as *multiplier resistors*. Note that as the applied voltage increases, the value of the multiplier resistor also increases, and the maximum current that is allowed to flow is limited to a safe value for the meter movement.

The complete AC voltmeter is shown in Figure 2-13B. Note that only one scale is used for all three ranges. The instrument is also equipped with test probes so you can connect it to a circuit. These test probes allow you to simply place them in contact with the circuit under test so you can make voltage measurements very quickly and efficiently.

When you use a voltmeter to measure a voltage, you must always connect the meter must in parallel with the voltage to be measured. It is not necessary to break the circuit to obtain a voltage measurement. For example, if you wish to measure the voltage produced by the AC voltage source shown in Figure 2-14A, you simply connect the meter in parallel with the source as shown. Since a resistor is also connected across the voltage source, the voltmeter is effectively measuring the voltage across the resistor as well as the source. Remember, voltage is constant across a parallel branch circuit. Assume that two resistors are connected in series and then connected across a voltage source. To measure the voltage across one of the resistors, connect your meter in parallel with the single resistor as shown in Figure 2-14B. To make your voltage measurement, simply connect (touching) the test probes to each side of the resistor. The voltage indicated by the meter is voltage across the single resistor.

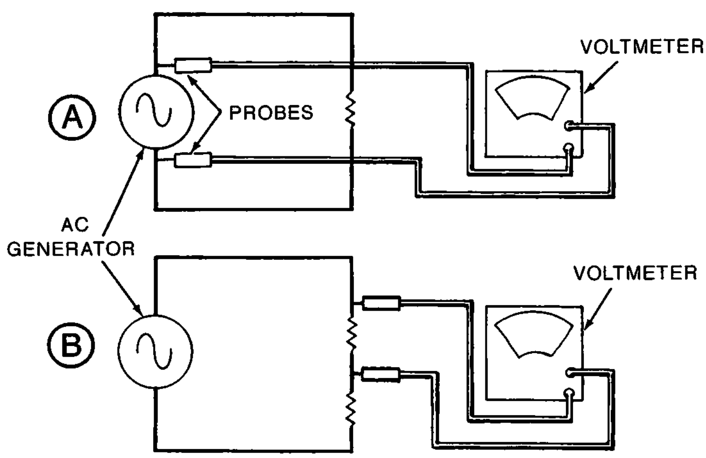


Figure 2-14
Measuring voltage with a voltmeter.

When you measure an AC voltage, it usually makes no difference which direction you connect the meter. You could interchange the test probes shown in Figure 2-14 and the voltage readings would not change. The AC voltage continually changes direction or polarity which makes it unnecessary to observe polarity.

CAUTION: One exception to this is when you measure voltages with a meter that has an earth-grounded reference lead. For example, electronic trainers that are earth grounded (3-prong line cords) and meters that are earth grounded. It is possible to insert a ground into the circuit under test. The point where the meter's reference lead is connected becomes earth ground.

Always be sure that the voltage is within the meter's capability. When in doubt, use the highest range possible and work your way down to a range that provides a midscale reading. In the case of a DC voltage, be sure to observe proper polarity.

MEASURING POWER

In AC circuits, you can measure electrical power with special types of AC meters. These instruments measure the effective (rms) values of current and voltage, internally compute the amount of power (I × E), and indicate its value on a calibrated scale. Electrical power is simply the rate at which electrical energy is used, and it is measured in units called watts. Calculating of power in AC circuits is somewhat more complex than in DC circuits. To determine the power that is being consumed by a component in a DC circuit, in the form of heat, you multiply the current through the component by the voltage drop across the component. This relationship is shown mathematically as:

$$P = I \times E$$

In this equation, the power in watts is equal to the current in amperes times the voltage in volts. AC power is usually represented as true power (effective-rms).

This same equation is also applicable to AC circuits as long as the circuit contains only resistance. In a purely resistive circuit, the product of I and E always equals P. However, AC circuits often contain properties such as inductance and capacitance which you will learn more about later. When these properties exist, the product of I and E does not provide a true indication of power. The resulting power can appear to be much higher than is actually the case. Since the power **appears** to be consumed by the inductive or capacitive components, it is called apparent power. *Apparent power is expressed in units called volt-amperes.*

An instrument that measures AC or DC power is called a *wattmeter.* Most wattmeters utilize a special type of meter movement called an *electrodynamometer* movement. This type of instrument always measures the true AC power that is used by a component or circuit. In other words, it can distinguish true power from apparent power.

A simple wattmeter is shown in Figure 2-15. Note that the meter uses two stationary coils which are in series and a moving coil. When you use this instrument to measure the AC power consumed by a load, its stationary coils are connected in series with the load in order to measure the load current. These stationary coils are wound around two iron cores. The iron cores become magnetized when current flows through the stationary coils, and they perform essentially the same functions as the permanent magnet pole pieces, that were used in the moving-coil meter movement described earlier. The moving coil is similar to the type used in the moving-coil meter movement. This coil is connected in parallel with the voltage across the load in order to measure the voltage drop across the load. When the stationary and moving coils are properly connected as shown in Figure 2-15, they both produce magnetic fields which interact and cause the moving coil and its attached pointer to deflect. The amount of deflection is proportional to the product of the load voltage and the load current. Therefore, the meter actually monitors the voltage and the current, and provides a scale reading calibrated in watts.

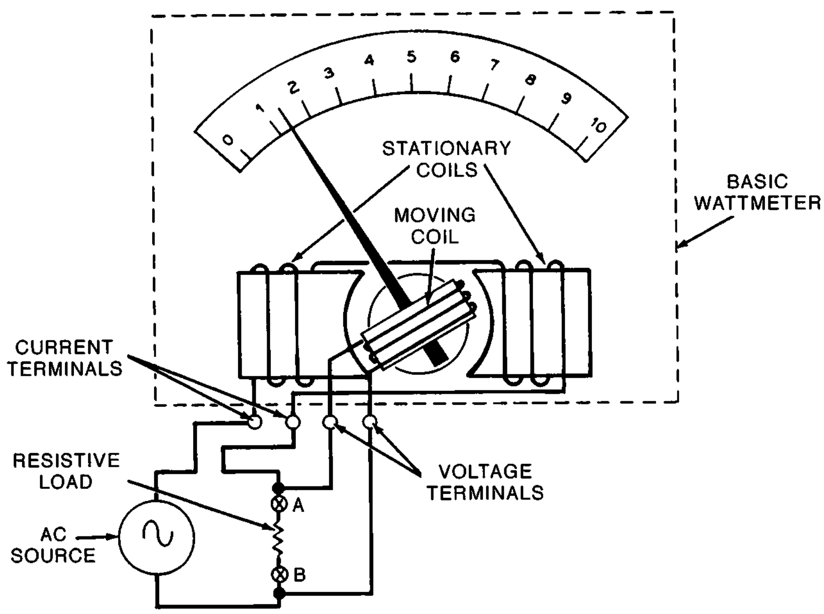


Figure 2-15
Measuring power with a wattmeter.

Most wattmeters provide reasonably accurate measurements and some are accurate to within ± 1%. These meters, like the ammeters and voltmeters that were described earlier, have internal resistance and therefore consume a certain amount of power themselves. Some wattmeters are calibrated to take their internal power loss into consideration while others are not. When you use meters that do not compensate for their own loss, you need to subtract the power used by the meter from the meter's reading. Manufacturers of these instruments sometimes indicate how much power is used by the meter. This information is in the form of correction data and is usually provided on a graph for a variety of power ratings at specific frequencies.

When you use an instrument that is not compensated and the manufacturer does not indicate the internal power loss, you can perform a simple test to determine the meter's internal loss. To do this, disconnect the load at points A and B as shown in Figure 2-15. Now, the stationary and moving coils are effectively in series and the meter measures its own internal power loss. For accurate readings, subtract this internal power reading from the reading you obtain with the load connected in order to obtain the actual true power dissipated by the load.

The stationary and moving coils in a wattmeter have specific current and voltage ratings respectively. Therefore, when you use a wattmeter you must be sure that you do not exceed the individual maximum current and voltage ratings of the device. Also, you must be careful not to exceed the maximum power that the device is designed to measure. If you exceed either of these ratings, the instrument can be permanently damaged.

Programmed Review

1.	Alternating currents and voltages may be measured by electromechanical devices called AC ___________ .
2.	(meters) One of the most widely used meters utilizes a moving-coil meter movement and a group of rectifiers and is called a ___________-___________ moving-coil meter.
3.	(rectifier-type) The moving-coil meter movement responds only to DC. Rectifiers are therefore needed to convert the AC input into a _________ output which can be applied to the moving coil in the meter movement.
4.	(DC) The moving coil in the meter movement operates in a manner similar to an electric motor. The moving coil rotates against the tension provided by the spiral springs, and the distance that it rotates is proportional to the amount of direct ____________ that flows through the coil.
5.	(current) A pointer is attached to the moving coil. Therefore, the pointer deflects a distance which is proportional to the current flowing in the ___________ coil.
6.	(moving) Like most AC meters, the rectifier-type, moving-coil meter utilizes a scale which is calibrated in ___________ values even though the meter responds to the average value of the AC applied.
7.	(effective) The numbers or values marked on the scale of the rectifier-type, moving-coil meters are equally spaced. Therefore, this type of meter has a ___________ scale.
8.	(linear) A moving-vane meter utilizes either a radial or a concentric iron vane which moves inside of a stationary _________ .

9. (coil) When current flows through the coil of a radial-vane meter, the moving-vane becomes magnetized along with a stationary vane which is located next to it. The two vanes become magnetized in the same direction so that the moving vane is forced to move away from the ____________ vane.

10. (stationary) The pointer is attached to the moving vane, therefore, the pointer deflects further as the current through the stationary coil ____________ in value.

11. (increases) The concentric-vane meter functions in a similar manner. However, the pointer in this meter is attached to a moving vane which is circular in shape. This circular shaped moving vane rotates when current flows through the stationary coil, which causes the __________ to deflect.

12. (pointer) Moving-vane meters provide a pointer deflection that increases with the square of the change in current and therefore have nonlinear scales. These scales are commonly referred to as __________-_________ scales.

13. (square-law) A thermocouple meter uses two dissimilar metal strips which are heated by the AC input current. These metal strips produce a DC output voltage which operates a __________-__________ meter movement.

14. (moving-coil) An AC meter that can measure the current through a conductor by simply clamping it around the conductor is called a __________-__________ meter.

15. (clamp-on) AC meters that are used to measure current may be calibrated in amperes, milliamperes, or microamperes. In general, these instruments are commonly referred to as __________.

16.	(ammeters) Many ammeters have more than one range. You can extend The range of an instrument by shunting a portion of the current around the meter. You do this with components known as ___________ resistors.
17.	(shunt) When you use an ammeter to measure current, you must connect the instrument in ___________ with the current to be measured so that the current flows through the meter.
18.	(series) You can also use an AC meter to measure voltage by connecting a resistor in series with the meter. Such a device is referred to as a ___________.
19.	(voltmeter) The range of a voltmeter is determined by the value of the resistor that is in series with the meter. A multiple-range voltmeter uses several of these resistors to multiply or extend its range. These series resistors are called ___________ resistors.
20.	(multiplier) When you measure voltage with a voltmeter, you must connect the instrument across the voltage to be measured. In other words the instrument must be connected in ___________ with the voltage source.
21.	(parallel) AC meters may also be used to measure power in watts. These meters are commonly referred to as ___________.
22.	(wattmeters) A wattmeter has two sets of input terminals. One set of terminals must be connected in ___________ with the current to be measured and the other set must be connected in ___________ with the voltage to be measured.
23.	(series, parallel)

OSCILLOSCOPES

AC meters can provide reasonably accurate measurements of current and voltage, but these instruments do not allow you to see what the AC quantities actually look like. In most cases, they are calibrated to indicate the effective or rms value of a sine wave. When you use them to measure nonsinusoidal waveforms, they do not provide true rms readings.

When you troubleshoot or analyze electronic equipment, it is often helpful or even necessary to know exactly what an AC waveform looks like. In many cases, it is necessary to know the peak and peak-to-peak values, instantaneous values, and the waveform's period. You can perform these measurements, as well as others, with a device known as an *oscilloscope*.

You can use an oscilloscope to analyze any type of AC waveform and measure its most important electrical characteristics. The oscilloscope, or *o'scope* as it is commonly called, is one of the most important test instruments used to measure AC quantities. The oscilloscope can also measure DC currents and voltages.

You will examine the operation of a basic oscilloscope and then consider some of the ways that you can use it to measure and analyze AC waveforms. Although this description is brief, it contains background information that should prove helpful.

Oscilloscope Operation

Oscilloscopes do not contain moving parts like the AC meters previously described. They are electronic test instruments that use various types of electronic circuits. Early oscilloscopes used vacuum tubes as the principal controlling elements in their electronic circuits. Newer oscilloscopes use semiconductor components such as transistors and solid state diodes in place of the larger tubes. The tube versions were much larger and required much more power to operate than the modern-day, solid-state oscilloscopes.

An oscilloscope can measure AC or DC voltages and display the voltage on a graph. The AC or DC voltage appears as a picture on a screen that is similar to the type of screen used in a television set. The main difference in the screen is that it is divided into equally-spaced, 1-centimeter squares. The oscilloscope contains a number of controls that allow you to adjust the size and the number of complete waveforms that are displayed. Most oscilloscopes are calibrated so that you can visually analyze the waveform, and easily determine its most important characteristics.

A simplified block diagram of an oscilloscope is shown in Figure 2-16. The device has two input terminals which are used to measure AC or DC voltages. These terminals are connected in parallel with the voltage source that is to be measured. They are generally referred to as the *vertical input terminals.* The AC voltage at these terminals is applied to an amplifier circuit which increases the amplitude or magnitude of the voltage before it is applied to a device known as a *cathode ray tube* or CRT. The CRT is the device which graphically displays the waveform that is present at the input terminals.

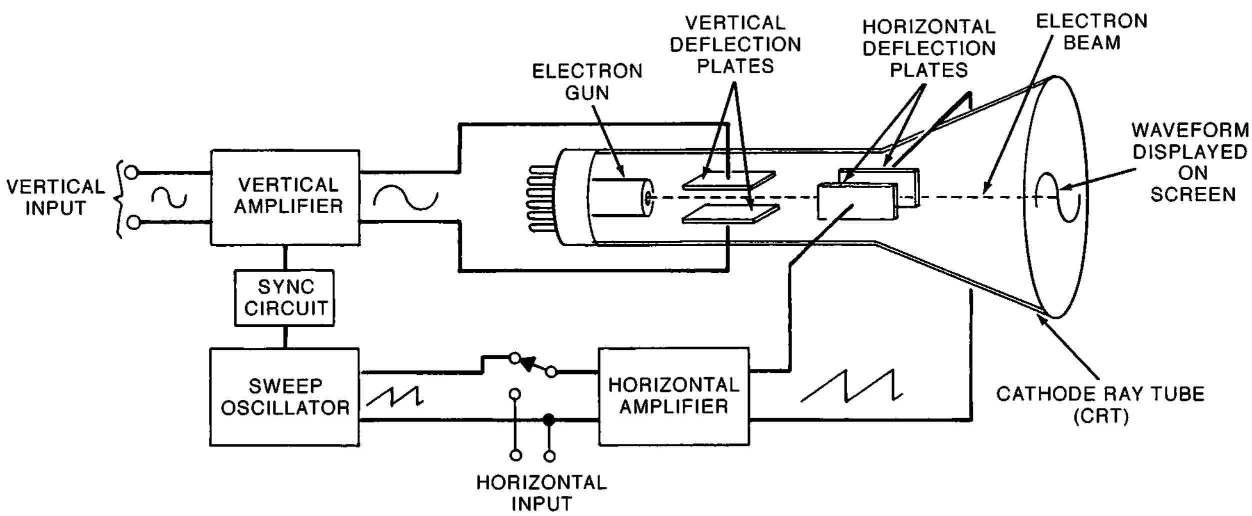


Figure 2-16
A basic oscilloscope.

As shown in Figure 2-16, a CRT contains an electron gun and two sets of deflection plates. These components are mounted inside a large glass tube which fans out at one end to form a screen which closely resembles the screen on a television picture tube. The air is pumped out of the tube and the end is sealed so the components operate within a vacuum. In this respect, the device is similar to an ordinary vacuum tube. The electron gun produces a stream of electrons which are focused into a narrow beam and aimed at the CRT screen. When the beam strikes the screen, it illuminates a phosphorus coating on the inside of the screen to produce a spot of light. The electron beam must pass between the two sets of deflection plates.

The AC voltage from the vertical amplifier is applied to the *vertical deflection plates.* This alternating voltage causes the plates to become positively and negatively charged and the polarity of these charges continually reverses. The electrons in the beam are negatively charged and tend to deflect toward the positive

plate and away from the negative plate which causes the beam to bend. Since the charges on the vertical plates continually change direction, the electron beam is deflected up and down to produce a vertical trace to appear on the CRT screen. The height of the vertical trace depends upon the amplitude of the AC voltage that is being measured and the amount of amplification provided by the oscilloscope's vertical amplifier circuit.

If the electron beam was simply moved up and down, only a vertical line or trace would appear on the screen. Such a display could indicate the peak-to-peak amplitude of a waveform, but still does not indicate the exact shape of the waveform. In order to show how the waveform's varies, it is necessary to move the electron beam horizontally across the screen. This is accomplished by a circuit known as a *sweep oscillator.* This circuit generates an AC sawtooth waveform which is then amplified by a *horizontal amplifier* and then applied to the *horizontal deflection plates.* The sawtooth voltage increases at a linear rate from a negative peak value to a positive peak value, and then almost instantly changes back to a negative value again. The positive and negative charges on the horizontal deflection plates vary in the same manner which causes the electron beam to move from left to right across the screen at a linear rate and then immediately jump back to the left side and start over again.

If only the sawtooth waveform is applied to the horizontal plates, with no voltage on the vertical plates, only the horizontal trace will appear on the screen. This trace is the *horizontal time base* that is used to measure the time of a waveform. The electron beam simply moves from left to right in a specific period of time and then repeats this action again and again.

When the vertical AC voltage and the horizontal sawtooth voltage are both applied to the CRT, an AC waveform can be produced. As the beam moves from left to right at a linear rate with respect to time, the vertical AC voltage causes the beam to move up and down in accordance with the variations in the AC voltage. If the time that is required for the beam to move across the screen from left to right is equal to generate one cycle of the AC input voltage, one cycle of the AC waveform will be displayed on the screen.

The relationship between the input AC sine wave, the sawtooth wave, and the displayed waveform is further illustrated in Figure 2-17. Note that one complete cycle of the sine wave (Figure 2-17A) occurs in the time required to generate one complete cycle of the sawtooth wave (Figure 2-17B). When these conditions are met, one complete AC sine wave is displayed as shown in Figure 2-17C. In other words, the frequency of the AC input waveform must be equal to the frequency of the sawtooth waveform. Furthermore, the sine wave and sawtooth wave must

begin their cycles at the same time in order to display a sine wave that is properly oriented as shown in Figure 2-17C. If the two waveforms are not properly synchronized (start at the same time), the displayed waveform might appear as shown in Figure 2-17D or Figure 2-17E. Although these waveforms are complete AC cycles, they are not properly oriented.

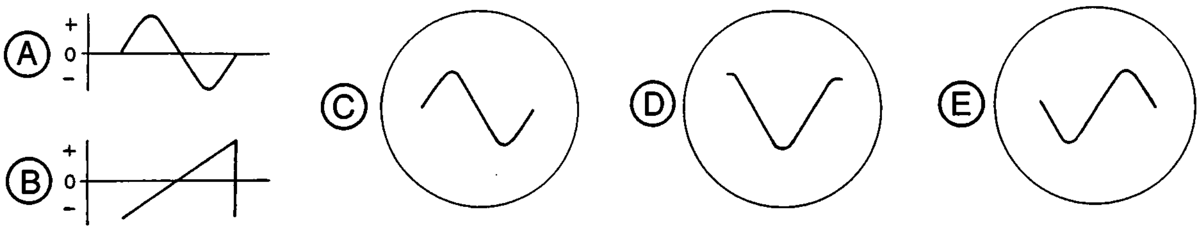


Figure 2-17
The input AC signal (A) and the sawtooth waveform (B) must have the same frequency for one cycle to be displayed (C).

To ensure that the input AC waveform and the sawtooth waveform are properly synchronized, a synchronization or sync circuit is included in the oscilloscope circuit. This circuit samples the incoming AC signal and produces a control signal that is applied to the sawtooth oscillator to make sure that the sawtooth generator begins its cycle at the proper time.

The input AC waveform and sawtooth waveform do not simply occur just once. These waveforms must occur repeatedly in order to produce a picture on the screen. In other words, the electron beam follows the pattern of the waveform again and again, and this results in a constant picture on the screen. The phosphor on the screen produces light for only an instant after the electron beam strikes it and moves on. Therefore, constant repetition is required to produce a pattern that is constantly illuminated.

Using the Oscilloscope

You can use the oscilloscope to observe and measure various types of AC waveforms. You will now briefly consider some of the ways in which this important test instrument can be used.

MEASURING VOLTAGE

Since the oscilloscope displays an entire AC waveform, it can be used to determine instantaneous values as well as peak and peak-to-peak values.

A typical oscilloscope display is shown in Figure 2-18. Note that the screen of the oscilloscope is marked with vertical and horizontal lines which form squares. This grid pattern is commonly referred to as a *graticule*. The squares are usually 1 centimeter high and 1 centimeter wide and represent a sheet of graph paper.

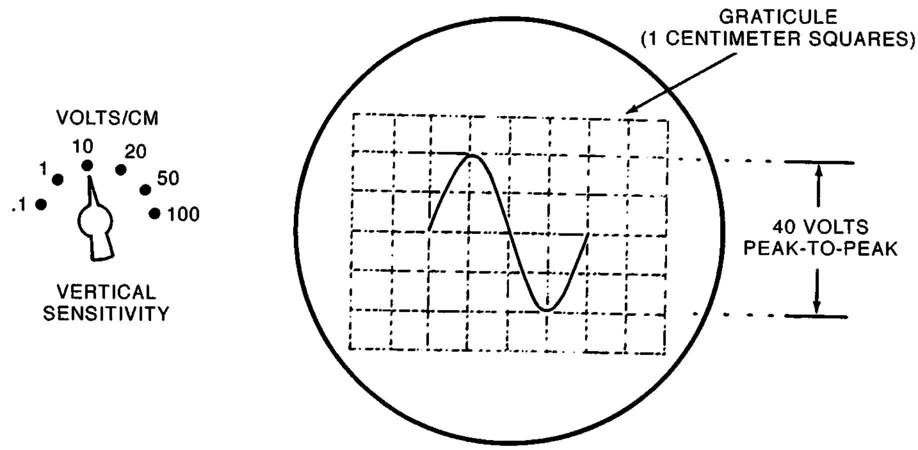


Figure 2-18
Measuring voltage with an oscilloscope.

Observe an AC waveform as shown in Figure 2-18. To adjust the vertical height of the waveform, you can use the vertical sensitivity control which varies the amplification factor of the vertical amplifier. Vertical (on-screen) deflection is directly proportional to given input voltage levels and the VOLTS/CM setting. The vertical amplification range selector is called a vertical sensitivity or vertical attenuator control. This control is calibrated to ensure accurate signal representation. For example, suppose the vertical sensitivity control is set to the 10 volts-per-centimeter (cm) position as shown in Figure 2-18. This means that each centimeter of vertical height or deflection represents 10 volts at the vertical input terminals. The waveform in Figure 2-18 is 4 centimeters high. Therefore, it has a peak-to-peak amplitude of 4 times 10 or 40 volts. The peak value of the waveform is equal to one half of 40 volts, or 20 volts. You can determine the value at any point along the waveform by comparing its relative position to the squares on the graticule and then multiplying your observation by the VOLTS/CM setting of the vertical sensitivity control.

Since the oscilloscope is capable of displaying and measuring the overall voltage of a waveform, the device is often referred to as a *peak-to-peak* measuring instrument.

Some less expensive oscilloscopes are not calibrated as shown in Figure 2-18. When you use this type of oscilloscope, it is necessary to apply a known DC or AC reference voltage to the vertical terminals and adjust the vertical amplifier for a specific amount of deflection. In other words, you calibrate the oscilloscope against a known voltage source. Then you may apply the unknown voltage and determine its value.

MEASURING THE PERIOD

The oscilloscope may be used to measure the period of an AC waveform. The period, or time for 1 cycle, is determined by observing the horizontal width of the waveform displayed on the screen. You can usually adjust the oscilloscope's sawtooth oscillator so that the electron beam moves from left to right across the screen at a specific speed. The time required for the beam to move horizontally across the screen is referred to as the *sweep time*. You use a control that is mounted on the oscilloscope to adjust the sweep time. This control sets the amount of time, in seconds, milliseconds, or microseconds that are required for the trace to move horizontally a distance of 1 centimeter.

Assume that the oscilloscope's sweep time control (TIME/CM) is set to the 5 milliseconds per centimeter position as shown in Figure 2-19. Each centimeter of horizontal deflection represents a time interval of 5 milliseconds. The waveform being displayed in Figure 2-19 is 4 centimeters wide. In other words, one complete cycle occupies 4 centimeters of the trace. The period of the waveform is equal to 4 times 5 milliseconds or 20 milliseconds.

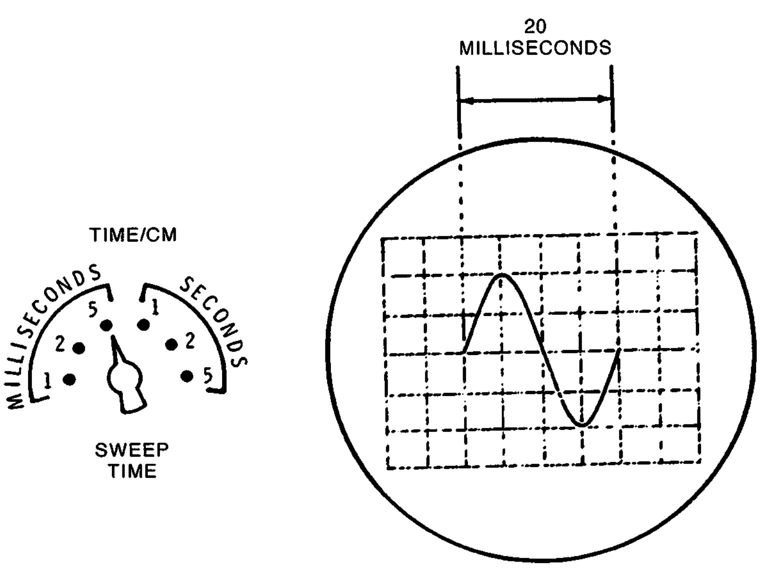


Figure 2-19
Measuring the period of an AC waveform.

You can set the oscilloscope's sweep time control to measure waveforms that have very long and very short periods. You simply adjust the control to produce at least one complete cycle of the AC signal on the CRT. Then, count the number of centimeters from the beginning to the end of the cycle and multiply that number by the sweep time.

In many cases, it is desirable to display only one cycle of a waveform, as shown. However, there are times when you need to observe more than one cycle, or a portion of a cycle. To show more than one cycle, you adjust the sweep time control for a shorter time period than you use to display one cycle of the AC signal. For example, suppose you need to measure an AC signal with a 1 millisecond period and you set the sweep time control for 1 millisecond-per centimeter. You will then see one complete cycle-per-centimeter across the CRT screen.

Naturally, to observe a portion of an AC cycle, you need to set the sweep time control for a longer time period than you use to display one cycle of the AC signal. In effect, you are magnifying a portion of the signal. For example, suppose the sweep time is 1 millisecond-per-centimeter and the CRT shows one complete cycle. Change the sweep time to 2 milliseconds-per-centimeter and you will see only one-half of a cycle.

An oscilloscope may therefore display a portion, one, or any number of input AC cycles. When a number of cycles are displayed on the screen, it is important to remember that it is necessary to only determine the time for one cycle in order to determine the period of the waveform.

MEASURING FREQUENCY

In order to determine the frequency of an AC waveform, you must know the period of the waveform. The frequency of an AC waveform is equal to 1 divided by the period of the waveform. In other words, time and frequency are reciprocal functions. Time is measured in seconds and frequency is measured in cycles per second. Frequency is measured in hertz and is expressed mathematically as:

$$f = \frac{1}{T}$$

For example, the waveform in Figure 2-19 has a period (T) of 20 milliseconds (0.02 seconds). This waveform has a frequency (f) of:

$$f = \frac{1}{0.02} = 50 \text{ Hz}$$

MEASURING PHASE RELATIONSHIPS

In some cases, it is necessary to compare two AC waveforms of the same frequency to determine if the two waveforms coincide or occur at the same time. In many cases, two AC waveforms within the same circuit are displaced in time, or by a given number of degrees. For example, a capacitor may shift an AC signal by approximately 90°.

If two AC waveforms coincide so that their instantaneous values both occur at the same time, they are *in phase* with each other. When the two waveforms are displaced (do not occur at the same time), they are *out of phase*. The amount of phase displacement is usually measured in degrees. For example, the AC sine wave shown in Figure 2-20B is in phase with the waveform in Figure 2-20A. The waveform in Figure 2-20C is 90° out of phase with the waveform in Figure 2-20A, and the waveform in Figure 2-20D is 180° out of phase with the waveform in Figure 2-20A.

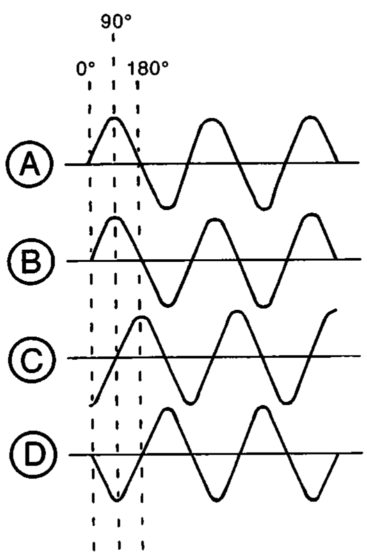


Figure 2-20
Phase relationships between AC sine waves.

In order to compare two AC sine waves and determine their phase relationship, it is necessary to apply one sine wave to the oscilloscope's vertical deflection plates and the other sine wave to the scope's horizontal deflection plates. To do this, you apply one waveform to the vertical input terminals and apply the other waveform to a set of horizontal input terminals on the scope. A switch is usually provided, as shown in Figure 2-16, which disconnects the sweep oscillator and connects the horizontal input terminals directly to the horizontal amplifier.

When both AC sine waves are properly applied to the scope, and the vertical and horizontal controls are properly adjusted, the electron beam will deflect in a manner that is determined by both AC waveforms. The resulting patterns displayed on the screen are referred to as *Lissajous patterns.* You can determine the phase relationship between the two waveforms by properly interpreting these unique patterns. A Lissajous pattern is defined as a shape that is undefined.

Several common Lissajous patterns are shown in Figure 2-21. These patterns occur at phase difference intervals of 45°, starting at 0° and extending to 360°. The pattern shown in Figure 2-21A occurs when both sine waves are in phase. This pattern is a diagonal line that extends from the lower left hand portion of the screen to the upper right hand portion. The pattern in 2-21B occurs when two waveforms are 45° out of phase. It is an oval or sometimes called an ellipse. At a phase difference of 90°, a perfect circle is formed as shown in Figure 2-21C. Then at 135° and 180° an ellipse and diagonal line are again formed as shown in Figure 2-21D and Figure 2-21E. However, these last two patterns are slanted in the opposite direction.

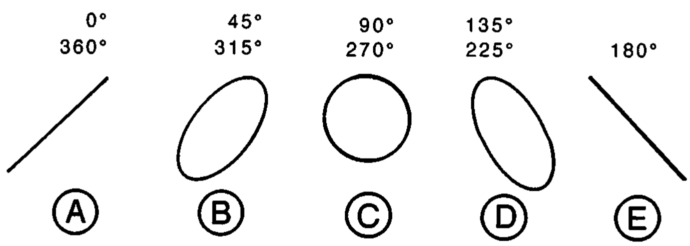


Figure 2-21
Typical Lissajous patterns.

Phase differences at values not shown in Figure 2-21 produce elliptical patterns that have shapes midway between the various shapes that are shown. It is important to realize that the Lissajous pattern changes from a diagonal line, to an ellipse, to a circle, then back to an ellipse, and finally back to a diagonal line as the phase difference increases from 0° to 180°. For phase differences between 180° and 360°, the sequence repeats but in the opposite direction as shown.

Lissajous patterns enable the oscilloscope to become a reasonably accurate phase-measuring device. However, the accuracy of the measurements taken depend largely upon the skill of the individual using the scope. Also, the waveforms must be sinusoidal in shape to produce the patterns shown in Figure 2-21. Nonsinusoidal waveforms produce irregular shaped patterns which are extremely difficult to analyze.

Programmed Review

24. An oscilloscope is capable of visually displaying an AC waveform on the screen of a ___________ _________ tube or CRT.
25. (cathode ray) To measure an AC voltage, you connect the oscilloscope's ___________ ___________ terminals in parallel with the AC voltage source.
26. (vertical input) The AC voltage applied to the scope is amplified and then applied to the vertical deflection plates in the CRT. These vertical plates cause an electron beam to move up and down and effectively paint a vertical trace on the ___________ of the CRT.
27. (screen) A sawtooth waveform is generated within the scope and applied to the horizontal deflection ___________ in the CRT.
28. (plates) The sawtooth waveform causes the electron beam to move horizontally across the screen. Since the beam moves at a linear rate, it produces what is commonly referred to as a ____________ time base.
29. (horizontal) When the input AC waveform and the ____________ waveform are both applied to the deflection plates, the input waveform is displayed on the CRT.
30. (sawtooth) You can use an oscilloscope to measure the peak-to-peak or peak voltage of a waveform because the instrument uses a graticule which has vertical and horizontal lines. The sensitivity of the instrument can be adjusted so that a specific number of volts at the input terminals cause the electron beam to move a specific distance on the ____________.
31. (graticule) If you adjust the scope so that it has a vertical sensitivity of 20 volts per centimeter and the waveform on the screen has a total vertical height of 6 centimeters, the AC waveform has a peak-to-peak value of _________ volts.

32. (120) You can measure the period of an AC waveform by observing the horizontal width of just one __________ of the waveform displayed on the screen.

33. (cycle) The time that is required for the beam to move a specific distance across the screen can be adjusted to make it possible to accurately measure the total __________ required for one cycle to occur.

34. (time) If the scope has been adjusted so that the beam requires 2 milliseconds to move 1 centimeter, and one cycle of the waveform on the screen has a width of 8 centimeters, the period of the waveform is __________ milliseconds.

35. (16) You can determine the frequency of an AC waveform with the equation $f = 1/T$. Therefore, if the period of the waveform is 16 milliseconds (.016 seconds), the frequency must be __________ Hz.

36. (62.5) It is also possible to determine phase relationships between sine waves with an oscilloscope. The scope produces Lissajous patterns that have distinct shapes which correspond to various __________ differences.

37. (phase)

RESISTANCE IN AC CIRCUITS

Now that you have examined some of the basic test instruments that you can use to measure AC values, you will analyze some fundamental AC circuits and the rules which apply to these circuits.

For now, you will study AC circuits which contain only resistance. First, you will learn about the relationship between current, resistance, and voltage, in these purely resistive circuits, and compare them to similar DC circuits. Later in this course, you will examine more complex AC circuits which contain additional properties such as inductance and capacitance. However, you must have a complete understanding of simple resistive circuits before you can advance to more complex concepts.

Basic AC Circuit Calculations

To form a basic AC circuit, you can connect a load resistance across an AC voltage source as shown in Figure 2-22A. Although a resistor is used in this circuit, any resistive component such as a lamp or heating element has the same effect. Such devices are, for all practical purposes, purely resistive and have a negligible amount of inductance or capacitance.

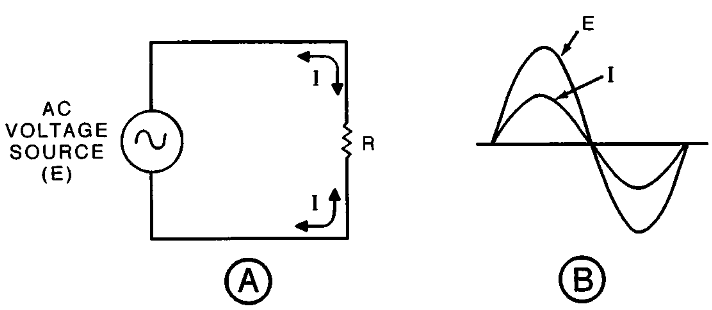


Figure 2-22
Current and voltage in a resistive AC circuit.

The voltage source could be an AC generator or an electronic circuit that produces an AC voltage. When this voltage is applied across the resistor, a corresponding AC current is produced that flows through the resistor. This current varies in amplitude and direction and is in phase with the applied AC voltage. In other words, the current is zero when the voltage is zero and it reaches its maximum when the voltage is maximum. When the voltage changes polarity, the current also changes direction. The voltage and current in a purely resistive AC circuit are *in phase*.

This phase relationship, between the voltage and current, is shown graphically in Figure 2-22B. The illustration shows that the voltage (E) waveform and the current (I) waveform pass through zero and maximum at the same time. Both E and I also change direction at the same time. The two waveforms do not have exactly the same peak amplitude because they represent different quantities and are measured in different units. They are drawn together only to show that they occur simultaneously.

The value of current flowing through the resistor in Figure 2-22A, at any given instant, depends upon the voltage at that instant and the circuit resistance, which remains constant. You can use Ohm's Law to determine the current at any instant just like you do for a DC circuit. In other words, the same rules and laws that apply to DC circuits also apply to AC circuits that are purely resistive.

Ohm's Law states that the voltage, current, and resistance are mathematically related as follows:

$$E = I \times R$$

This equation states that voltage, which is measured in volts, is equal to current, which is measured in amperes, times the resistance, which is measured in ohms.

You can rearrange this basic equation to show that current is equal to voltage divided by resistance. This is expressed mathematically as:

$$I = \frac{E}{R}$$

You can also rearrange it to show that resistance is equal to voltage divided by current and expressed mathematically as:

$$R = \frac{E}{I}$$

When you work with AC circuits, you will seldom use instantaneous values of voltage and current in AC calculations. In most cases, you will use the effective values of these quantities instead. As you learned earlier, the effective value of an AC voltage or current sine wave is equal to 0.707 times its peak or maximum value. An AC current sine wave with an effective value of 1 ampere effectively produces the same amount of heat in a given resistance as a DC current of 1 ampere. Therefore, when you use effective values you are expressing the AC quantity in terms of its DC equivalent value.

You can use Ohm's Law with effective values just as easily as with instantaneous values. In other words, you obtain the effective value of E if you multiply the effective value of I by R. Likewise, you can determine the effective value of I when you divide the effective value of E by R. Also, R is equal to the effective value of E divided by the effective value of I.

Consider a typical circuit that has an AC voltage source with an effective value of 100 volts and a resistance of 100 ohms, as shown in Figure 2-23. According to Ohm's Law, the effective value of current (I) is equal to:

$$I = \frac{E}{R} = \frac{100 \text{ volts}}{100 \text{ ohms}} \text{ or 1 ampere}$$

Therefore an effective voltage (force) of 100 volts causes an effective current of 1 ampere to flow through a resistance of 100 ohms.

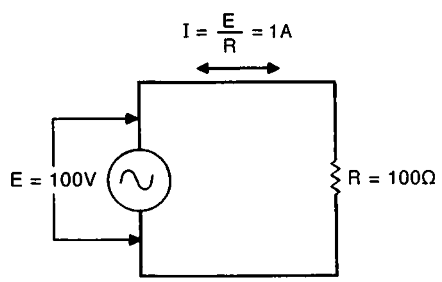


Figure 2-23
Finding the effective value of an AC current.

Now consider a circuit in which you know resistance and current and you must determine the voltage. For example, in Figure 2-24 the current has an effective value of 3 amperes and a resistance equal to 50 ohms. According to Ohm's Law, the applied voltage must have an effective value of:

$$E = IR = (3 \text{ A})\ (50 \text{ ohms}) = 150 \text{ volts}$$

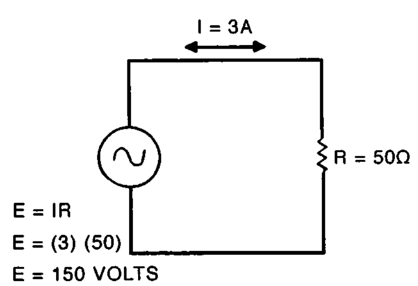


Figure 2-24
Finding the effective value of AC voltage.

Series AC Circuit Calculations

The current in a purely resistive circuit is always in phase with the applied voltage, even when more than one resistor is used. For example, the single resistor shown in Figure 2-22A could be replaced with two series resistors so that a simple series circuit is formed as shown in Figure 2-25A. The current flowing through a circuit is limited by the total resistance of the circuit which is the sum of the two resistances. This current has the same value, at any given instant, at all points in the circuit. Also, this current is in phase with the applied voltage. This in-phase relationship between the applied voltage, E_A, and circuit current is shown in Figure 2-25B.

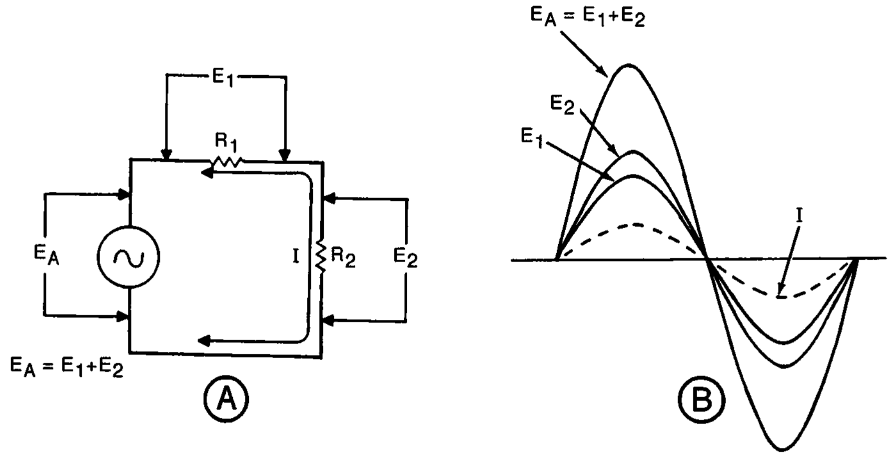


Figure 2-25
Current and voltage in a series circuit.

Since the current flows through both R_1 and R_2, there is a voltage drop across each resistor. The voltage drop across each resistor at any given instant is equal to the product of the circuit current at that instant and the resistor's value. The two voltages, designated as E_1 and E_2, are in series, and when you add together their instantaneous values, the total equals the applied voltage at that specific instant. In other words, E_1 and E_2 are in phase with E_A, and their combined values, $E_1 + E_2$, is always equal to E_A. This in-phase relationship between E_A, E_1, and E_2 is shown in Figure 2-25B. Note that all three of these voltages are in phase with each other and they are also in phase with the circuit current.

As you learned earlier, it is common practice to use effective values of current and voltage when you analyze AC circuits. To illustrate this point, consider a typical series AC circuit. Suppose that the AC voltage source has an effective value of 150 volts and that R_1 and R_2 have values of 50 ohms and 100 ohms

respectively as shown in Figure 2-26. The total resistance of the circuit, R_T is equal to $R_1 + R_2$. Therefore, R_T equals 50 ohms + 100 ohms or 150 ohms. The circuit contains a single 150 ohm resistor as far as circuit current is concerned. Therefore, the current equals E_A divided by R_T or:

$$I = \frac{150 \text{ volts}}{150 \text{ ohms}} = 1 \text{ ampere}$$

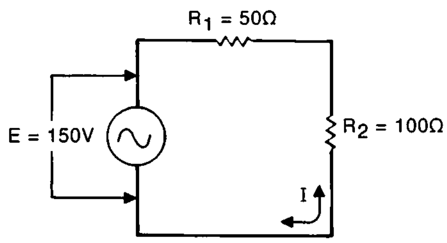


Figure 2-26
Calculating current and voltage in a series circuit.

This current value of 1 ampere represents the effective value of circuit current. The current flows through R_1 produces a voltage drop which, according to Ohm's Law, is equal to the circuit current times the resistance of R_1 or:

$$E_1 = IR_1 = (1A)\ (50 \text{ ohms}) = 50 \text{ volts}$$

This same current flows through R_2 and produces a voltage across this resistor of:

$$E_2 = IR_2 = (1A)\ (100 \text{ ohms}) = 100 \text{ volts}$$

Note that these voltage drops are proportional to the resistor's values. Also, these voltages are expressed in effective values. The sum of these two effective voltages equals the effective value of the applied voltage. This is expressed mathematically as:

$$E_A = E_1 + E_2 = 50 \text{ V} + 100 \text{ V} = 150 \text{ volts}$$

This example shows how effective AC values are used in a simple series AC circuit. As you can see, these effective values are used the same way that DC values are used. The same rules that apply to a series DC circuit, that contains only resistance, also apply to a series AC circuit which contains only resistance.

Parallel AC Circuit Calculations

When two resistors are connected in parallel and an AC voltage is applied to them as shown in Figure 2-27A, the total current (I_T) supplied by the voltage source is in phase with the applied voltage (E_A). This in-phase relationship between E_A and I_T is shown in Figure 2-27B. However, the total current divides and flows through the two resistors R_1 and R_2. These two currents are designated as I_1 and I_2 in Figure 2-27A.

The individual currents are in phase with I_T, and their instantaneous values add to produce I_T as shown in Figure 2-27B. Therefore, at any given instant I_T equals the sum of I_1 and I_2.

The applied voltage appears across both resistors, and this voltage is in phase with currents I_T, I_1, and I_2 as indicated in Figure 2-27B.

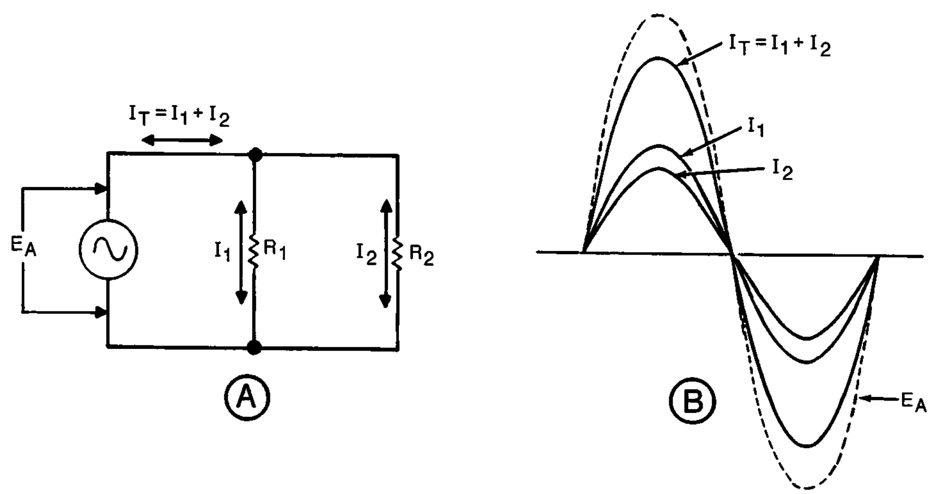


Figure 2-27
Current and voltage in a parallel circuit.

To illustrate how you use effective values when to analyze the parallel circuit in Figure 2-27, consider a typical parallel circuit. Suppose that the applied voltage is 150 volts and R_1 and R_2 have values of 50 ohms and 100 ohms respectively as shown in Figure 2-28.

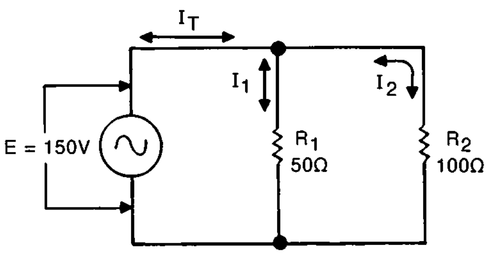


Figure 2-28
Calculating current and voltage in a parallel circuit.

To determine the value of branch current I_1, divide the applied voltage by the branch resistance (R_1). The value is:

$$I_1 = \frac{150 \text{ volts}}{50 \text{ ohms}} = 3 \text{ amperes}$$

The current through R_2 is the same applied voltage divided by R_2:

$$I_2 = \frac{150 \text{ volts}}{100 \text{ ohms}} = 1.5 \text{ amperes}$$

Total current (I_T) is the sum of the branch currents:

$$I_T = I_1 + I_2 = 3 \text{ A} + 1.5 \text{ A} = 4.5 \text{ amperes}$$

Since the total current is 4.5 amperes and the applied voltage is 150 volts, you can again use Ohm's Law to determine the equivalent or total resistance of the circuit. In other words, the total resistance is:

$$R_T = \frac{150 \text{ volts}}{4.5 \text{ amperes}} = 33.3 \text{ ohms}$$

The circuit functions as if it contains one resistor that has a value of 33.3 ohms. If you connect a resistor with this value across the voltage source, the total current will be the same.

All of the current and voltage values that were just used are effective values. You use them in exactly the same way as you use DC current and voltage values in DC parallel DC circuit.

You can calculate the total resistance of a parallel circuit with the reciprocal formula for resistors connected in parallel. The formula is:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_N}}$$

This reciprocal formula works for any number of resistors that are connected in parallel.

When you have only two resistors connected in parallel, you can use the product over the sum method to calculate the total resistance like this:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

When all of the resistors that are connected in parallel have the same value, you can simply divide the value of one resistor by the total number of resistors that are connected in parallel:

$$R_T = \frac{\text{the value of one resistor}}{\text{number of resistors in parallel}}$$

The last method that you can use to calculate total resistance in a parallel circuit is called the *assumed voltage method.* In this method, you do not need to know the actual value of the applied voltage or the branch currents. You assume a voltage (use a voltage that you can evenly divide by each of the resistors that are in parallel whenever practical). Next, divide the assumed voltage by each branch resistance to obtain the individual assumed branch currents. Now add the calculated branch currents to obtain an assumed value for I_T. The last step to determine R_T with the assumed method is to divide the assumed voltage by the assumed total current. This results in the actual total resistance of the paralleled resistors.

Power in AC Circuits

In an AC resistive circuit, power is consumed by the resistive component in the form of heat, just like it is in a DC resistive circuit. The power in either a DC or AC circuit is measured in units called *watts*.

In a DC circuit, power in watts is equal to current in amperes times voltage in volts. The following equation shows this relationship mathematically:

$$P = IE$$

The same relationship applies to AC circuits which contain only resistance. In other words, you can multiply the current at a specific instant by the voltage of that instant to determine the instantaneous power. After you multiply all of the instantaneous values for a complete cycle of voltage and current, you find that the power curve follows the voltage and current changes. In other words, AC power is proportional to the product of voltage and current at any point on their curves.

A simple AC circuit is shown in Figure 2-29. The power consumed by the resistor in this circuit varies with the product of the current through the resistor and the voltage dropped by the resistor. The relationship between power, current, and voltage is shown in Figure 2-29B. Note that the power curve, or waveform, does not extend below the zero axis (horizontal line). This is because the power is effectively dissipated in the form of heat, no matter which direction current flows, and it is assumed to have a positive value. Note that power reaches its peak value when both E and I are maximum. Likewise, power drops to zero when both E and I equal zero.

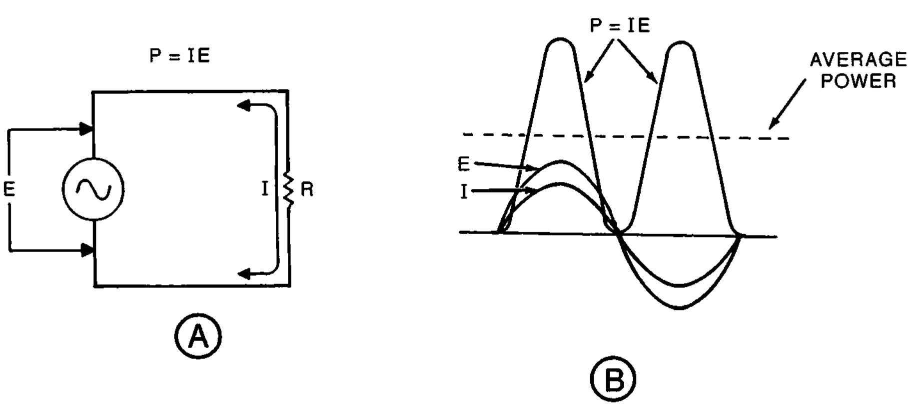


Figure 2-29
Power in an AC circuit.

Since the power fluctuates between a peak value and zero, the average power that is used by the circuit is midway between these two extremes. In other words, if you draw a line midway between the peak and zero values, the line will indicate the average power being used. It is average power that is most important in AC circuits. Average power is the power that is actually used in AC circuits.

To calculate the average power dissipated in an AC circuit, multiply the effective value of current times the effective value of voltage. Therefore, you can use the power equation, P = IE, in AC calculations as long as you use the effective values of I and E. For example, suppose the resistor in Figure 2-29 has a value of 100 ohms and the applied voltage has an effective value of 100 volts. The current in the circuit is:

$$I = \frac{100 \text{ volts}}{100 \text{ ohms}} = 1 \text{ ampere}$$

You multiply the effective current value of 1 ampere by the effective value of the applied voltage as follows:

$$P = IE = (1 \text{ A})\,(100 \text{ V}) = 100 \text{ watts}$$

The resistor consumes (dissipates in the form of heat) 100 watts of power.

At times, it is convenient to use another form of the power equation that expresses power in terms of voltage and resistance. This equation states that power is equal to the voltage squared (E^2) divided by the resistance and is stated mathematically as:

$$P = \frac{E^2}{R}$$

You could have used this form of the power equation to solve the previous problem. It eliminates the step that calculates the current through the resistor.

You can also express the power equation in terms of current and resistance as:

$$P = I^2R$$

This equation simply states that power is equal to the current squared times the resistance.

The various forms of the power equation provide several means of calculating power. You can use combinations of known values of current, voltage, and resistance to find unknown values. These equations also work for DC circuit calculations.

Programmed Review

38. When an AC voltage is applied to a resistor, the current that flows through the resistor varies in accordance with the AC voltage. Therefore the AC current and the AC voltage are __________.

39. (in phase) You can use Ohm's Law to determine the current at any given instant. In other words, the current at a given instant depends upon the __________ at that instant and the circuit resistance.

40. (voltage) When you calculate AC values, instantaneous values are seldom used. Instead, it is common practice to use the __________ values of the currents and voltages involved.

41. (effective) If an effective voltage (E) of 100 volts is applied to a resistance (R) of 25 ohms, the current through the resistor has an effective value of ________ amperes according to Ohm's Law (I = E/2).

42. (4) In a series circuit which contains more than one resistor, the current in the circuit is still in phase with the applied __________.

43. (voltage) The voltages dropped across each resistor in the series circuit are in phase with each other and with the applied voltage. At any given instant, the sum of these voltage drops is equal to the applied __________.

44. (voltage) If a series circuit contains a 10 ohm resistor (R_1) and a 20 ohm resistor (R_2) which are connected to an applied voltage (E_A) that has an effective value of 90 volts, the circuit allows an effective current of ________ amperes to flow according to Ohm's Law.

45. (3) When two resistors are connected in parallel, the current through each resistor (I_1 and I_2) is in phase with the voltage (E) applied to these resistors. These individual currents are in phase and they combine or add to produce a total __________ (I_T).

46. (current) If an effective voltage (E) of 200 volts is applied to two parallel resistors, and the currents through these resistors have effective values of 3 and 7 amperes respectively, the total current (I_T) in the circuit has an effective value of _________ amperes.

47. (10) The circuit just described has a total or equivalent resistance (R_T) of _________ ohms according to Ohm's Law.

48. (20) You can easily determine the power in a resistive circuit by multiplying the effective values of voltage times the effective value of ___________.

49. (current).

EXPERIMENT 1

Measuring AC Voltages

OBJECTIVES: *To demonstrate how you use an AC voltmeter to measure AC voltages.*

To show the relationship between AC voltage and current in a series circuit.

To illustrate that Kirchhoff's Voltage Law applies to AC circuits.

Introduction

In this experiment, you will construct a series-resistive circuit on your Trainer and measure the AC voltages that appear in the circuit. You will use Kirchhoff's and Ohm's Laws to perform calculations and compare your calculated values with your measured values.

The 15 VAC (15-volt AC) source on your trainer provides the AC voltage for this experiment. Figure 2-30 shows a typical front panel area where you might obtain this voltage. Note that there are two 15-volt AC sources. Terminal 2 is a common ground for these sources. Also, remember that all of the indicated voltage values are effective voltage values.

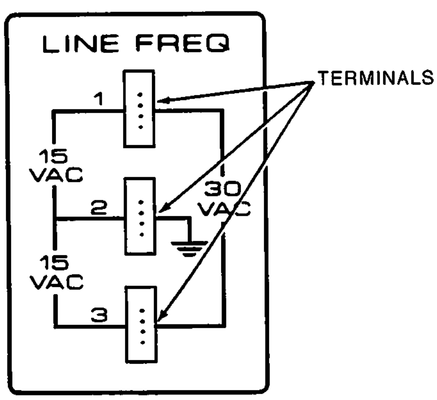


Figure 2-30
This area of your Trainer provides the AC voltages for these experiments.

Before you begin this experiment, read the instructions provided with your voltmeter to be sure that you understand how to change voltage ranges and interpret the indications on the different voltage scales. Also review the operations and applications section of the manual for your Trainer.

Material Required

Heathkit Analog Trainer
AC Voltmeter
1 — 470 Ω, 1/2-watt resistor (yellow-violet-brown)
2 — 1 kΩ, 1/2-watt resistors (brown-black-red)

Procedure

1. Be sure that the POWER switch on your Trainer is in the off position. Then plug in your Trainer's line cord.

2. Construct the circuit shown in Figure 2-31. To do this, follow the wiring diagram shown in Figure 2-32. This circuit contains a 1000 ohm resistor designated as R_1, a 470 ohm resistor, R_2, and a 1000 ohm resistor, R_3. These three resistors are connected in series. The AC voltage applied to these resistors has an effective value of approximately 15 volts.

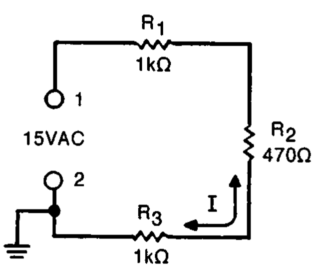


Figure 2-31
Experimental circuit.

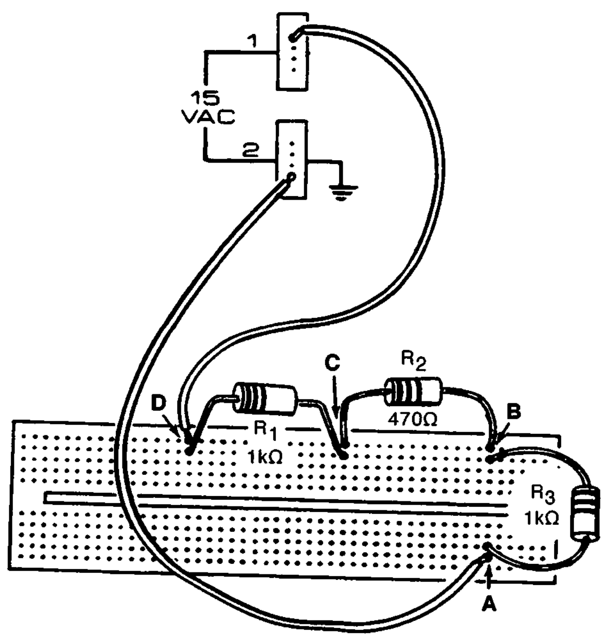


Figure 2-32
Wiring diagram for experimental circuit.

3. Turn on your Trainer. Measure the 15 VAC applied voltage with your voltmeter. When you do this, be sure that the meter ground is connected to the circuit ground at terminal 2. Although AC meters are not normally polarity sensitive, it is necessary to observe polarity in this and the following experiments because both the negative lead of the meter and the Trainer may share the same earth ground.

   The voltage that you measure may be slightly greater or less than 15 volts. Indicate the applied voltage, E_A, in the blank provided below.

   $E_A =$ __________ volts.

4. Use Ohm's Law to calculate the current in the circuit. First, add R_1, R_2, and R_3 to find the total resistance. The total resistance is equal to:

   $R_T = R_1 + R_2 + R_3 =$ __________ ohms

   Now divide the applied voltage measured in step 3 by the total resistance to calculate the current, I. Record your answer in the blank below.

   $I = \frac{E_A}{R_T} =$ __________ amperes

5. Now use Ohm's Law to calculate the voltage drops across resistors R_1, R_2, and R_3. Enter your answers below.

   $E_1 = I \times R_1 =$ __________ volts

   $E_2 = I \times R_2 =$ __________ volts

   $E_3 = I \times R_3 =$ __________ volts

6. Now, observe polarity and measure the voltage across resistor R_3. To do this, connect the negative lead (usually the black probe or a ground clip) to the grounded side of resistor R_3 at point A in Figure 2-32, and the positive meter lead (usually the red probe) to the other side of R_3 at point B. Record the voltage in the blank provided below.

   $E_3 =$ __________ volts

   Is this the same voltage value that you calculated for E_3 in step 5? __________.

7. Measure the voltage drop across resistors R_2 and R_3. Leave the meter negative lead in place at point A and move the positive lead to point C. The voltage measured at point C is:

$$E_{2+3} = \_\_\_\_\_\_\_\_\_\_ \text{ volts}$$

Now subtract the voltage drop across R_3 from the voltage drop across R_2 and R_3 to calculate the voltage drop across R_2.

$$E_2 = E_{2+3} - E_3 = \_\_\_\_\_\_\_\_\_\_ \text{ volts}$$

Is this voltage the same as the voltage that you calculated for E_2 in step 5?

__________.

8. Now measure the voltage drop across the entire circuit. To do this, leave the ground lead in place while you connect the other lead to point D in Figure 2-32. Write the value of this voltage in the space provided below.

$$E_A = \_\_\_\_\_\_\_\_\_\_ \text{ volts}$$

Now subtract the voltage drop across R_2 and R_3 from E_A to calculate the voltage drop across R_1. The voltage drop across R_1 is:

$$E_1 = E_A - E_{2+3} = \_\_\_\_\_\_\_\_\_\_ \text{ volts}$$

Is this the same as the voltage drop that you calculated for R_1 in step 5?

__________.

9. What is the reason for any deviation between the voltage values you calculated in step 5 and the actual values you obtained from the voltage measurements? ____.

10. Turn off the Trainer and read the following discussion.

Discussion

After you constructed the series circuit in this experiment, you measured the applied voltage, E_A. The nominal value is 15 VAC but the voltage supplied by your trainer may have been slightly above or below this value. The following explanation uses the 15 VAC nominal value.

Next you used Ohm's Law to determined the current through the circuit. First you added the values of the individual resistances in the circuit to determine the total resistance, R_T. This value should be 2470 ohms.

Then, you divided the applied voltage by the total resistance to calculate that the current, I, is approximately .006 amperes or 6 milliamperes.

You next used this current and the various resistor values to calculate the voltage drops across the resistors. These are approximately:

$$E_1 = 6\text{ V}$$

$$E_2 = 2.8\text{ V}$$

$$E_3 = 6\text{ V}$$

In steps 6, 7, and 8, you determined the actual voltage drops across the resistors. These probably did not correspond to the values that you calculated in step 5. There are two reasons for this.

First, a certain amount of error is inherent in any meter. Typically, analog AC meters are accurate to within plus or minus 5%. If you use a digital meter, generally speaking, your results will be somewhat more accurate.

Second, the components in the circuit have tolerances of plus or minus 5%. This, combined with the tolerance in meter accuracy, can at times cause significant variations between calculated and measured values.

With Kirchhoff's Voltage Law you were able to compare calculated voltages to measured voltages. Kirchhoff's Voltage Law: around a closed loop, the sum of the voltage drops is equal to the sum of the voltage rises. Another way of saying the same thing is: around a closed loop, the algebraic sum of all the voltages is zero.

$$E_A - E_1 - E_2 - E_3 = 0\text{ V}$$

EXPERIMENT 2

The Oscilloscope

OBJECTIVES: *To demonstrate the operation of an oscilloscope.*

To show how to use an oscilloscope to determine period, frequency, amplitude, and shape of an AC signal.

To demonstrate the phase relationship between current and voltage in an AC circuit.

To show how to measure and calculate peak, effective, and peak-to-peak values.

Introduction

Read this entire experiment before you begin to perform it. You will use an oscilloscope to measure the outputs from the Heathkit Analog Trainer. In addition, you will use information from your oscilloscope to make a number of calculations. This experiment is designed to help you understand AC sine wave characteristics.

You will study both the 15 VAC LINE FREQUENCY and AC signals from the GENERATOR section of your trainer. Figure 2-33 shows a typical front panel area where you can obtain these voltages and signals. Your trainer model may vary slightly from this illustration, but you should easily recognize these sections. Take a moment to locate each section. The 15 VAC terminal is described in Experiment 1. The GENERATOR section can supply either sine or square waves that, in most cases, vary in frequency from 200 Hz to 20 kHz.

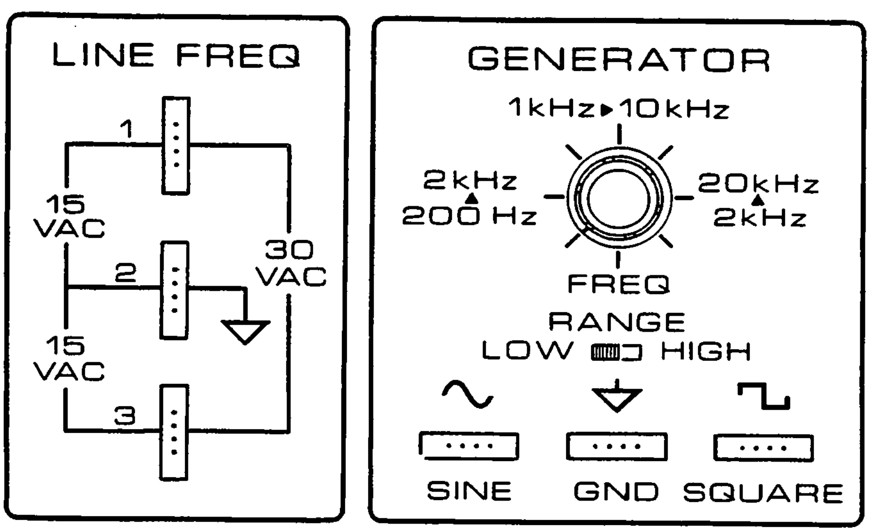


Figure 2-33

Before you begin this experiment, review the operation and applications section of your Trainer Manual.

Before you apply power to your oscilloscope, you should make certain adjustments. These adjustments begin on page 2-62 under "Procedure."

The locations and labels for the controls shown in Figure 2-34 are for a two-input (dual-trace) Heathkit Oscilloscope. Since the oscilloscope terminology is relatively standard, you should have no problem converting these instructions to any other oscilloscope.

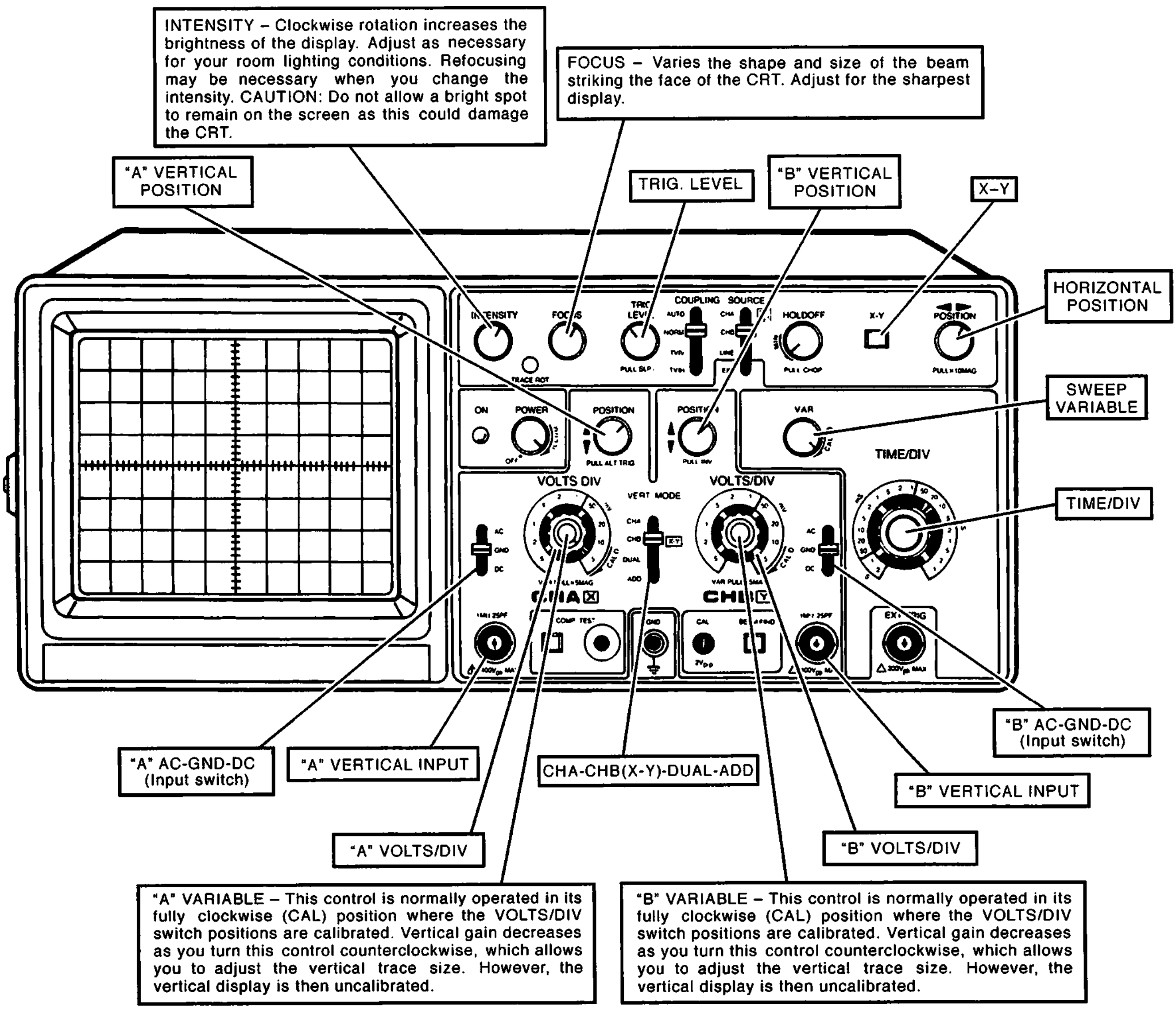


Figure 2-34

Material Required

Heathkit Analog Trainer
Dual-trace oscilloscope with a X10 (times ten) probe for the Channel A Vertical input, and a second probe, or test cable, for the Channel B Vertical input.
1 — 100 Ω, 1/2-watt resistor (brown-black-brown)
1 — 1 kΩ, 1/2-watt resistor (brown-black-red)
1 — .01 μF capacitor
1 — 47 kΩ, 1/2-watt resistor (yellow-violet-orange)

Procedure

NOTE: The following steps were written for a dual-trace oscilloscope. If you have a single-input oscilloscope, some controls may be labeled differently.

1. Turn the INTENSITY control to midrange.

2. Set the TRIGGER SOURCE switch to the CHA position.

3. Set the TRIGGER COUPLING switch to the AUTO position.

4. Set the TIME/DIV control to the 2 mS position and the SWEEP VARIABLE to CAL.

5. Set the HORIZONTAL POSITION control to midrange.

6. Set each AC-GND-DC switch to the GND position.

7. Set each VOLTS/DIV control to 1V and its VARIABLE to CAL.

8. Set the VERTICAL MODE switch to CHA.

9. Set the VERTICAL POSITION control to midrange.

10. Connect the oscilloscope to the proper power source.

11. Turn the POWER switch ON.

12. Allow the oscilloscope to warm up for one minute, then adjust the VERTICAL POSITION and HORIZONTAL POSITION controls to center the sweep on the scope.

13. Adjust the FOCUS control for a sharply focused presentation.

Discussion

Your oscilloscope is now ready to measure an AC signal. At this time, however, all you see is a single horizontal sweep, or trace. That's because there is no signal applied to the channel A (channel 1) vertical input—the input is grounded.

Procedure (Continued)

14. Set the CHANNEL A AC-GND-DC switch to the AC position.

15. Attach the X10 probe to the CHANNEL A INPUT of the oscilloscope, or "scope." Make sure the probe's switch is set to X10.

WARNING: In the following step, be sure that the ground clip is NOT connected to pin 1 or pin 3. This would directly ground the output of the power transformer and blow the Trainer's power fuse.

16. On the Trainer, use a short jumper wire to connect the probe tip to either Pin 1 or Pin 3 of the Line Frequency output. Connect the ground clip from the probe to the center tap ground, Pin 2, of the Line frequency output. The connection is shown in Figure 2-35.

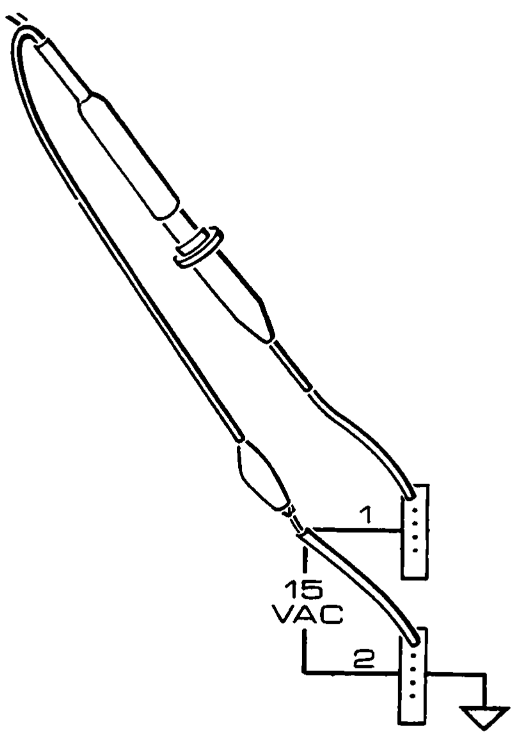


Figure 2-35

17. Make sure that the TIME/DIV control is set to the 2 mS-per-division position. If you do not have a 2 mS position, any setting of this control which gives from one to three complete waveforms on the scope display is adequate for this experiment.

18. Make sure the CHANNEL A VARIABLE control is in its calibrate position.

19. Make sure the SWEEP VARIABLE control is in the calibrate position.

20. Make sure the TRIGGER COUPLING control is set to the AUTO position. You should now have a presentation similar to the one shown in Figure 2-36.

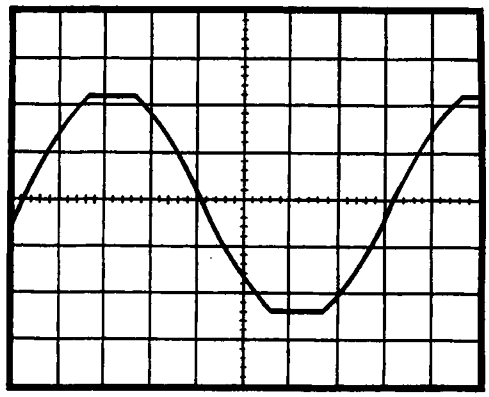


Figure 2-36

Discussion

The waveform shown on your oscilloscope is a sample of the line frequency signal that is applied to the power supply of the Trainer. The clipping, or smoothing, of the peaks of this signal is due to the saturation of the transformer core in the Trainer output during current peaks. This has no major effect on the next portion of this experiment. (In some Trainers, this clipping does not occur.)

Procedure (Continued)

21. Determine the horizontal width, in centimeters, of one cycle of the wave form displayed on the oscilloscope screen. The signal is __________ cm long.

22. Now determine the period of the waveform displayed on the screen. The period is __________ milliseconds (mS).

    (If you have any difficulty with the preceding two steps, refer to the discussion on Page 2-37 of your text).

23. Now that you have determined the period of the AC waveform, it is possible to calculate the frequency of the signal. The frequency is __________ Hz.

    (If you have any difficulty determining the frequency, refer to the discussion on Page 2-38 of your text).

24. Refer to the waveform on your oscilloscope. Use the horizontal and vertical controls to display a waveform presentation in the center of the screen, that has equal positive and negative alternations. Determine the height of one alternation of the waveform in centimeters. The height is _________ cm.

    If you have any problem with this or the following two steps, refer to the Discussion on Page 2-36.

25. Use the height of the AC waveform from the previous step to calculate the peak amplitude of the AC waveform. The peak amplitude of the signal is __________ volts.

26. Now, calculate the peak-to-peak voltage of this AC signal. The peak-to-peak voltage is __________ volts.

27. Refer to the peak voltage you calculated in step 25. Is there any difference between this value and the stated 15 VAC output from the Trainer? ________ If so, why is there a difference? ______________________________

    ____

    ____.

Discussion

Each graticule on the face of the oscilloscope is 1 centimeter by 1 centimeter. To determine the horizontal width of one cycle of an AC waveform, count the number of graticules which are encompassed by a cycle. In the case of the example waveform, the signal is about 8.3 cm long.

After you determine the width of the waveform, multiply the width by the setting on the TIME/DIV control to determine the period of the signal. During the experiment, the TIME/DIV control was set at 2 mS. Therefore, the period of the signal is:

$$8.3 \times 2 \text{ mS} = 16.6 \text{ mS}$$

Once you know the period of the signal, you use the following equation to calculate the frequency:

$$f = \frac{1}{t} = \frac{1}{16.6 \text{ mS}} = 60 \text{ Hz}$$

This is the line frequency of the signal supplied by the Trainer. You can use the preceding method to calculate the frequency of any AC signal.

The United States has a standard line frequency of 60 Hz. Although many foreign countries use a standard of 50 Hz, you can assume that your experiments maintain a 60 Hz line frequency, unless otherwise called for in an experiment.

It is also possible to calculate the amplitude of an AC signal with an oscilloscope. To do this, you must first know the height of one peak of the AC waveform. The peak height of the 15 VAC output is between 2.1 cm and 2.2 cm when the oscilloscope is set for 1 volt-per-division and you use a X10 probe.

Once you know the height, it is a simple matter to determine the actual peak voltage. Just multiply the height of the signal in centimeters by the setting on the VOLTS/DIV control setting. Remember to compensate for the reduced signal level when you use an X10 probe—multiply the reading by ten.

$$2.1 \text{ cm} \times 1 \text{ volt-per-division} \times 10 = 21 \text{ volts}$$

Since 21 volts is the peak voltage, you can multiply the peak value by 2 to determine the peak-to-peak value:

$$21 \text{ volts} \times 2 = 42 \text{ volts p-p}$$

The peak-to-peak voltage of the waveform is 42 volts.

The calculated peak voltage of 21 volts is significantly larger than the 15 VAC that is indicated as the output of the power supply. This is because the output of the power supply is given in effective volts. To calculate the effective voltage of a signal that has a 21 volt peak, multiply 21 volts by .707:

21 volts peak × .707 = approximately 15 volts effective

Remember that unless it is otherwise stated, AC voltages are always presented as effective (rms) values in documents and on equipment.

Procedure (Continued)

28. Construct the circuit shown in Figure 2-37. For now, connect the sine wave generator output, at the wiper arm of the 1 kilohm pot, to point B in the circuit.

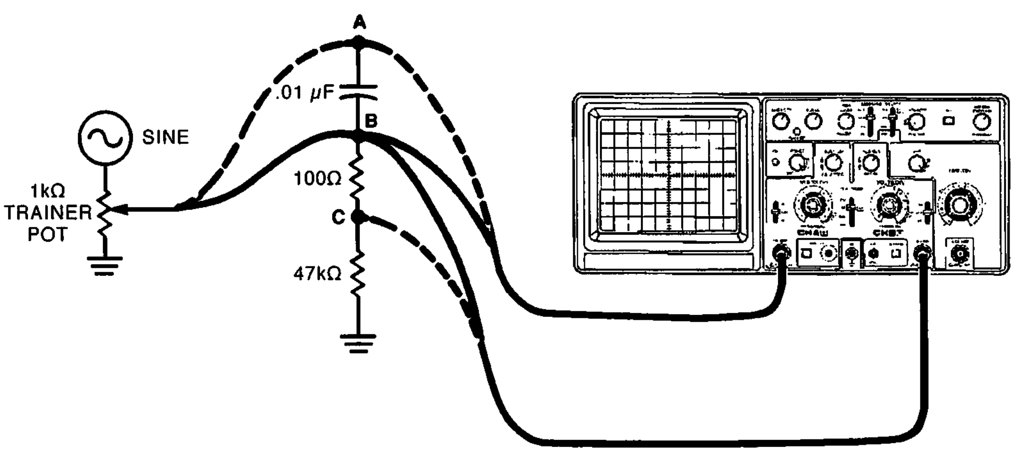


Figure 2-37

29. Adjust the Trainer Generator section for a sine wave with a frequency of approximately 2 kHz and center the 1 kilohm pot.

30. Preset your oscilloscope probes as follows:

    Both VOLT/DIV switches to 2V and their VARIABLE controls to CAL
    Both AC-GND-DC switches to GND
    Connect probes to both vertical inputs (probe switch to X1)
    Depress the X-Y switch
    Set the VERTICAL MODE switch to X-Y (CHB)

31. Connect the oscilloscope Channel A vertical input to point B in the circuit. Then, connect the oscilloscope Channel B vertical input to point B.

    The X-Y mode is used in place of the normal scope time base so you can observe Lissajous patterns on the display. In the X-Y mode, the scope's internal sweep generator is disabled. Therefore, you will see a dot on the screen. You can use the HORIZONTAL POSITION control to move the dot horizontally, and Channel B's VERTICAL POSITION control to move the dot vertically.

32. Use the HORIZONTAL and Channel B VERTICAL POSITION controls to center the dot on the screen.

33. Set the Channel A AC-GND-DC switch to DC. You should see a horizontal line that is approximately 4 centimeters long.

34. Return the Channel A switch to GND and set the Channel B AC-GND-DC switch to DC. You should now see a vertical line that is approximately 4 centimeters long.

    In the X-Y mode, the signal you apply to the channel B vertical input controls X-axis deflection. The signal you apply to the channel A vertical input controls Y-axis deflection. You may have noticed that the Channels on your oscilloscope are labeled X and Y. The length of the vertical or horizontal line that is displayed is determined by the amplitude of the input signals and the settings of the VOLTS/DIV switches. That's how you produce a Lissajous pattern on an oscilloscope display. You use one signal to control vertical deflection and a second signal to control horizontal deflection.

35. Set the Channel A AC-GND-DC switch to DC and observe the display. Use the 1 kilohm pot on the Trainer to adjust the length of the waveform to approximately 5 divisions.

36. Use the oscilloscope's vertical and horizontal controls to center the waveform on the display. What does the waveform look like? ______________

    ____

37. Move the probe coming from the scope's Channel A input from point B to point C in the circuit. What happened to the waveform? ______________

    ____

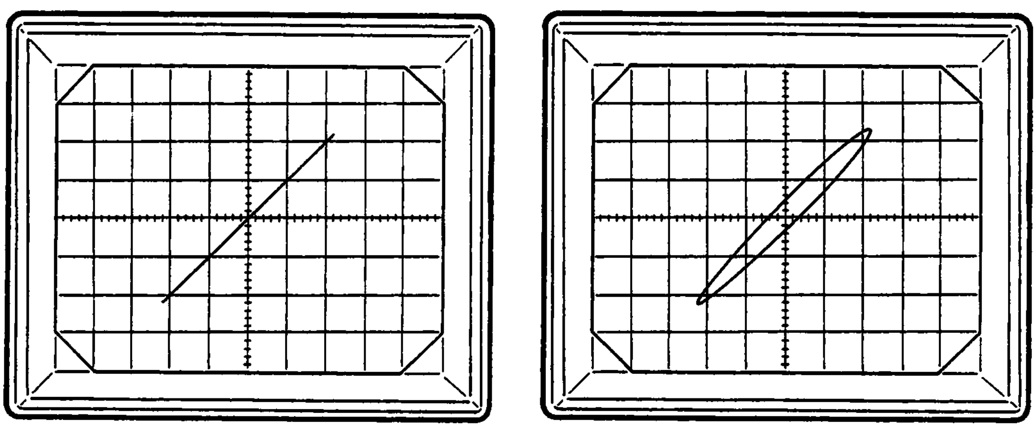
38. Move the wire coming from the wiper of the 1 kilohm pot from point B to point A. Then, move the probe coming from the scope's Channel A vertical input from point C to point A in the circuit. What happened to the waveform? ____

____

39. Switch the Trainer off and remove the circuit components from the Trainer.

Discussion

In this portion of the experiment, you measured the phase difference between two sine waves, one represented voltage and the other current. You began by establishing a reference. You applied two identical sine waves to the X and Y scope inputs to setup a 45-degree Lissajous pattern, or waveform, on your scope. Because both VOLT/DIV switches were set to 2V/division, the signals produces equal vertical and horizontal deflection, which resulted in a 45-degree reference trace. Ideally, you should have see a straight line as shown in Figure 2-38A. What you may have seen was a very thin ellipse which indicates a small amount of phase shift. This is caused by improperly matched scope probes. Each probe induces a small amount of delay, or phase shift, due to its internal capacitive and inductive reactance. You'll learn more about these characteristics later in the course.



A B

Figure 2-38

In Step 37, you moved the probe coming from the scope's Channel A input to point C in the circuit and observed the change in phase when an AC signal passes through a resistor. The voltage at point B was the input voltage and the voltage at point C was the voltage drop across the 100 ohm resistor. Thus, you can see any current phase shift in the voltage at point C. If you looked very carefully, you might have seen a slight rotation of the waveform, but no change in its shape. The rotation was simply caused by the small voltage drop across the resistor, not by any current phase shift. True phase shift only shows up as a change in the shape of the Lissajous pattern.

Finally, in Step 38 you added a capacitor to the circuit and observed its effect on the phase of the current through the circuit. This time, the scope showed a pattern that is similar to the one in Figure 2-38B. This told you that the capacitor changed the phase of the current in relation to the applied voltage. Later, you will learn more about how capacitors and other circuit components change the phase of an AC signal. You will also observe other Lissajous patterns on your oscilloscope.

SUMMARY

A variety of AC meters are used to measure both AC current and AC voltage. One of the most popular types is the rectifier-type, moving-coil meter, although moving-vane meters, thermocouple meters, and clamp-on meters are also used.

A meter that is used to measure current is called an ammeter. Normally an ammeter must be connected in series with the current to be measured. The circuit under test must be turned off while you connect the ammeter into the circuit. Only the clamp-on ammeter can be used without breaking the circuit under test. This meter clamps over the conductor and measures magnetic field strength. The field strength is then converted and displayed as a current. The clamp-on ammeter is used in applications that require high currents.

The oscilloscope is perhaps the most versatile of all test instruments. It can measure peak, peak-to-peak, and other instantaneous waveform values. This instrument can also be used to measure the period and frequency of a waveform as well as compare AC sine waves and determine their phase relationships, frequencies, and amplitudes.

You can analyze AC circuits which contain only resistance in much the same way as DC circuits which contain only resistance. When you analyze AC circuits, it is common practice to use effective values of the currents and voltages involved.

UNIT EXAMINATION

The following multiple choice examination is designed to test your understanding of the material presented in this unit. Place a check beside the multiple choice answer (A, B, C, or D) that you feel is most correct. After you complete the examination, compare your answers with the correct ones that appear after the exam.

1. Which of the following AC meters utilizes a linear scale?

   A. The radial-vane meter
   B. The thermocouple meter
   C. The rectifier-type, moving-coil meter
   D. The concentric-vane meter

2. An AC meter that is used to measure current is referred to as an:

   A. ammeter only.
   B. ammeter, milliammeter, or microammeter.
   C. AC voltmeter.
   D. AC wattmeter.

3. Except for the clamp-on type ammeter, you must connect all other types of AC ammeters:

   A. so that current flows through them in the proper direction.
   B. across the component whose current is to be measured.
   C. in series with the current to be measured.
   D. in parallel with the current to be measured.

4. You can use any AC ammeter to measure AC voltage as long as:

   A. a resistor is connected in parallel with the meter movement.
   B. it does not have a radial-vane meter movement.
   C. it does not have a square-law scale.
   D. you connect it in series with a multiplier resistor.

5. If a meter has a square-law scale and the current through the meter increases to 5 times its initial value, the meter's pointer will deflect:

   A. 5 times its initial distance.
   B. 10 times its initial distance.
   C. 15 times its initial distance.
   D. 25 times its initial distance.

6. You can use a shunt resistor to extend the range of a (an):

   A. DC ammeter but not an AC ammeter.
   B. ohmmeter.
   C. ammeter.
   D. voltmeter.

7. In order for a wattmeter to measure power, it must measure:

   A. both current and resistance.
   B. both current and voltage.
   C. both voltage and resistance.
   D. current, voltage, and resistance.

8. You can use an oscilloscope to perform:

   A. frequency, period, and phase measurements only.
   B. peak and peak-to-peak measurements only.
   C. peak-to-peak, frequency, and period measurements only.
   D. frequency, period, phase, peak-to-peak, and instantaneous measurements.

9. When you observe the vertical height of the waveform displayed on an oscilloscope's graticule, it is possible to determine the:

   A. peak-to-peak value of the waveform.
   B. frequency of the waveform.
   C. period of the waveform.
   D. phase relationship between the waveform displayed and a second waveform that is applied to the scope's horizontal terminals.

10. When observe the horizontal width of the waveform on a graticule which is calibrated in units of time, it is possible to determine the:

    A. peak value of the waveform.
    B. period of the waveform.
    C. peak-to-peak value of the waveform.
    D. phase relationship between the waveform displayed and a second waveform that is applied to the scope's horizontal terminals.

11. When you analyze AC circuits, it is common practice to use:

    A. peak current and voltage values.
    B. peak-to-peak current and voltage values.
    C. effective current and voltage values.
    D. effective current values and peak voltage values.

12. The currents and voltages in an AC circuit which contains only resistance:

    A. cannot be calculated according to Ohm's law.
    B. cannot be evaluated by using the same rules which apply to DC circuits.
    C. are out of phase.
    D. are in phase.

EXAMINATION ANSWERS

1. C — The rectifier-type, moving-coil meter uses a linear scale which has equally spaced values. The meter pointer deflects a distance that is directly proportional to the current flowing through the moving coil.

2. B — AC meters that are used to measure current are often called ammeters, milliammeters, or microammeters when they are used to measure current in the ampere, milliampere, or microampere range.

3. C — Ammeters must be connected in series with the current to be measured. This means that it is usually necessary to break the circuit under test so that you can insert the ammeter.

4. D — A multiplier resistor limits the current through the meter to the proper value.

5. D — The pointer deflection will increase with the square of the current. Since the current increases 5 times, the deflection will increase by 5 squared (5^2) or 25 times.

6. C — Shunt resistors can be connected in parallel with AC or DC meters to extend their current range.

7. B — Wattmeters produce a pointer deflection that is proportional to the product of the current and the voltage.

8. D — You can perform all of these measurements with the oscilloscope, as long as the person using the scope is properly trained.

9. A — You can determine peak-to-peak, peak, and instantaneous values in this manner.

10. B — You can use this method to determine the period, which you can then use to determine the frequency.

11. C — Effective values of current and voltage are used because they are equivalent to DC values. In other words, an effective AC current value of 1 ampere is equivalent to 1 ampere of DC current because both produce the same amount of heat when they flow through a given resistance. You can conveniently use effective values to calculate the actual power that is consumed in a resistive AC circuit.

12. D — This in-phase relationship between current and voltage exists in any purely resistive circuit.

Unit 3

CAPACITIVE CIRCUITS

CONTENTS

INTRODUCTION

In this unit you will study capacitors, capacitance, and the effects of capacitance on an AC circuit. You should already be familiar with capacitors from your study of DC electronics. However, to refresh your memory, the first part of this unit is devoted to a review of capacitors and capacitance.

In the remainder of the unit you will study the effects of capacitance on an AC circuit. The relationship between voltage and current in a capacitive circuit is discussed in detail. In addition, some practical applications of basic capacitive circuits is presented.

The concepts presented in this unit are very important to your understanding of AC electronics. Study this unit carefully; be sure to complete all questions and perform all of the experiments.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Explain what a capacitor is.
2. Explain how a capacitor operates.
3. List the basic units of capacitance and convert from one unit to another.
4. Discuss the factors that effect capacitance.
5. List the most commonly used types of capacitors.
6. Calculate the total capacitance of capacitors connected in series and in parallel.
7. Explain the most common ways in which capacitors fail.
8. Define the term phase shift.
9. Draw a diagram that illustrates the phase relationship between the current and voltage in a capacitive circuit.
10. Define capacitive reactance and compute its value in ohms when you know the capacitance in farads and the operating frequency.
11. Discuss the phase and voltage relationships in a series resistor/capacitor circuit.
12. Discuss the phase and current relationships in a parallel resistor/capacitor circuit.
13. Define the term impedance and calculate the impedance of series and parallel resistive/capacitive circuits.
14. List several practical applications for the simple series resistor/capacitor circuit.
15. Calculate the cut-off frequency for a series resistor/capacitor circuit.
16. Use trigonometry to solve RC circuit problems.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "Review of Capacitors and Capacitance."	________
☐ Read "Review of Capacitors and Capacitance."	________
☐ Complete Programmed Review Frames 1-47.	________
☐ Read "Capacitors in AC Circuits."	________
☐ Complete Programmed Review Frames 48-72.	________
☐ Read "RC Circuits."	________
☐ Complete Programmed Review Frames 73-101.	________
☐ Perform Experiments 3 and 4.	________
☐ Read "Applications of Capacitive Circuits."	________
☐ Perform Experiment 5.	________
☐ Complete Programmed Review Frames 102-132.	________
☐ Complete the Unit Examination.	________
☐ Check the Examination Answers.	________

REVIEW OF CAPACITORS AND CAPACITANCE

Before you learn how capacitors arc used in alternating current circuits, it is desirable to review the basic operation and characteristics of a capacitor. You can understand the operation of a capacitor in an A C circuit better if you are familiar with the operation of capacitors in DC circuits. This section reviews the key facts about capacitors.

A capacitor is a passive electronic component that stores electrical energy in the form of an electrostatic field. In its simplest form, a capacitor consists of two conducting plates separated by an insulator called the dielectric. Figure 3-1 shows a simple capacitor. It has two square metal plates that are separated by an air dielectric.

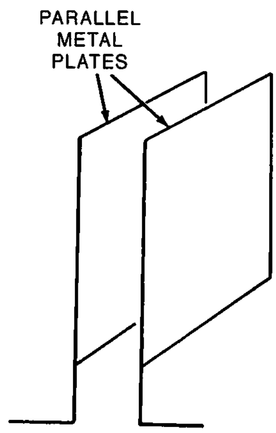


Figure 3-1
A simple capacitor.

When you apply a DC voltage to the plates of a capacitor, the capacitor becomes charged. Figure 3-2A shows a battery connected to the simple two-plate capacitor. The positive terminal of the battery attracts electrons from the left-hand plate of the capacitor, which leaves the left--hand plate with a positive charge. Electrons from the negative terminal of the battery move on to the right-hand plate, which gives it a negative charge. In this state, the capacitor is charged. Since the positive and negative electrical charges on the plates attract one another, a force field is set up between the two plates. However there is no electrical current now

through the capacitor due to the insulating dielectric between the two plates. The only time current flows is when you initially connect the battery. Current flow, or movement of electrons, takes place only during brief instant of time that it takes for the capacitor to charge. Once the capacitor is charged to a value approximately equal to the DC source voltage, current ceases to flow.

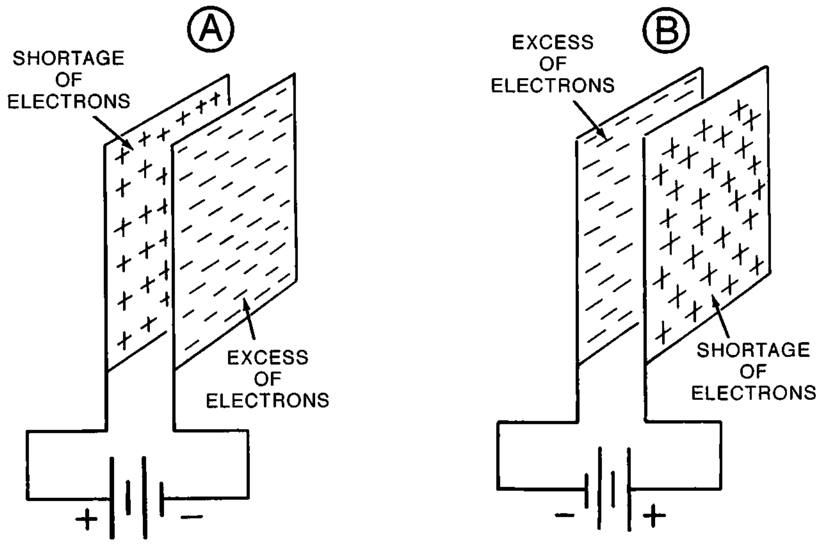


Figure 3-2
Charging a capacitor with a battery.

Most capacitors can be charged in either direction. Figure 3-2B shows how you can charge the two plate capacitor in the opposite direction by interchanging the battery leads. In this state, the left-hand plate takes on a negative charge and the right-hand plate takes on a positive charge. When a capacitor starts to charge, current is maximum. As the difference of potential between the battery and capacitor charge becomes less and less, current decreases until the capacitor's charge equals the applied voltage. At this instant, there is no difference of potential and current ceases to flow.

When you remove the battery in the circuits shown in Figure 3-2 from the capacitor, the electrical charges on the plates remain. The attraction of the positive and negative charges on the two plates across the dielectric holds the charges in place and the capacitor remains charged. As long as the two plates are insulated from one another, the capacitor will remain charged.

You can discharge the capacitor by shorting the plates together. To do this, connect a wire between the plates as shown in Figure 3-3. When you short a capacitor in this way, the electrons on the negative plate flow through the shorting wire to the positively charged plate. Electrons again flow momentarily to create a current. The excess of electrons on the right-hand plate neutralize the positive charge on the left-hand plate. This discharge action gives the capacitor a neutral or zero charge. When a capacitor discharges, initially current flow is maximum and decreases as the charge (difference of potential between the plates) decreases. Once the plates are neutralized, current ceases to flow.

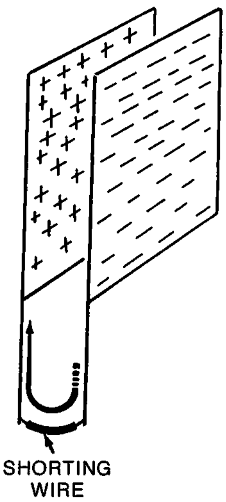


Figure 3-3
Discharging a capacitor
by shorting the plates.

As you can see, a capacitor can store electrical energy in the form of a charge. The capacitor is charged by an external voltage source, then retains that charge because the dielectric keeps the oppositely charged plates separated. The capacitor discharges when a path for current physically connects the two oppositely charged plates. The charge is, therefore, neutralized. No current flows through the capacitor itself, but current does flow in a capacitive circuit during both charge and discharge times of the device. You can best understand this concept if you think of the available current flowing to the negative plate during charge; then through the shorting connection, from that plate, to the positive plate during discharge. Figure 3-4 shows the electronic symbols that are used to represent capacitors in schematic diagrams of electronic circuits.

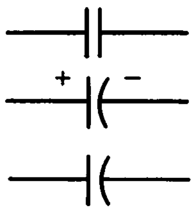


Figure 3-4
Schematic symbols for a capacitor.

The ability of an electronic component to store an electrical charge is referred to as capacitance. Components that exhibit this characteristic are known as capacitors. Most capacitors have two leads, each attached to a plate, which are separated by a dielectric. However, capacitance can exist in any situation where two conductors are separated by an insulator. For example, capacitance exists between an insulated wire running near a metal chassis. The chassis represents one plate of the capacitor while the wire represents the other plate. The insulation of the wire and any air space between the two conductors represents the dielectric. Capacitance not in the form of a physical component is generally referred to as distributed or stray capacitance. It exists in all electronic circuits and greatly affects their operation, especially at high frequencies.

Units of Capacitance

The measure of a capacitor's ability to store an electrical charge is its capacitance. The unit of capacitance is the farad. One farad of capacitance indicates that a capacitor stores one coulomb of charge when the voltage applied to the capacitor is one volt. This relationship is expressed below:

$$C = \frac{Q}{E}$$

C equals the capacitance in farads, Q equals the quantity of the electrical charge expressed in coulombs (one coulomb = 6.25×10^{18} electrons), and E represents the applied voltage in volts. This expression tells you that the larger the quantity of electrons that a capacitor stores for a given applied voltage, the greater its capacitance. A large capacitor is capable of storing a large charge even when you apply a small voltage. A small capacitor cannot hold a large charge even if you apply a large voltage to it. The capacitance is a function of the physical characteristics of the capacitor.

The farad is a very large unit of measure. A one-farad capacitor is physically very large. A capacitor of this size is much larger than is required in most electronic applications. Most capacitors that are used in electronic circuits have capacitances in the microfarad range. Typical capacitors have a capacitance of one millionth of a farad or less. One millionth of a farad is called a microfarad (abbreviated μF). Another commonly used unit of capacitance is the picofarad (pF) which is one millionth of a microfarad. Table 3-1 shows the relationship between the farad, microfarad, and picofarad.

Table 3-1

Units of Capacitance

1 farad = 1,000,000 or 10^6 microfarads

1 farad = 1,000,000,000,000 or 10^{12} picofarads

1 microfarad = .000001 or 10^{-6} farad

1 microfarad = 1,000,000 or 10^6 picofarads

1 picofarad = .000000000001 or 10^{-12} farad

1 picofarad = .000001 or 10^{-6} microfarad

farad = F
microfarad = μF
picofarad = pF

The following examples below show you how to use Tables 3-1 and 3-2 to convert from one unit of capacitance to another:

1. Convert 25 μF to farads:
   25 μF = 25×10^{-6} = $25 \times .000001$ = .000025 F

2. Convert 470 pF to farads:
   470 pF = 470×10^{-12} = $470 \times .000000000001$ = .00000000047 F

3. Convert 1000 pF to microfarads:
   1000 pF = 1000×10^{-6} = $1000 \times .000001$ = .001 μF

4. Convert .00082 μF to pF:
   .00082 μF = $.00082 \times 10^{6}$ = $.00082 \times 1{,}000{,}000$ = 820 pF

Table 3-2

Converting Units of Capacitance

TO CONVERT	TO	ACTION
Farads	Microfarads	Multiply by 1,000,000 (10^6) or move the decimal point 6 places to the right.
Farads	Picofarads	Multiply by 1,000,000,000,000 (10^{12}) or move the decimal point 12 places to the right.
Microfarads	Farads	Divide by 1,000,000 (10^6) or multiply by .000001 (10^{-6}). Move the decimal point 6 places to the left.
Microfarads	Picofarads	Multiply by 1,000,000 (10^6) or move the decimal point 6 places to the right.
Picofarads	Farads	Divide by 1,000,000,000,000 (10^{12}) or multiply by .000000000001 (10^{-12}). Move the decimal point 12 places to the left.
Picofarads	Microfarads	Divide by 1,000,000 (10^6) or multiply by .000001 (10^{-6}). Move the decimal point 6 places to the left.

Factors That Affect Capacitance

The ability of the capacitor to store an electrical charge is referred to as capacitance. The capacitance of a capacitor is determined by its physical characteristics. Specifically, capacitance is determined by the total area of its plates, the distance that separates the plates, and the type of dielectric.

The larger the plates in a capacitor, the greater the charge that the capacitor can store. Larger plates can store more electrons and have more electrons to give up than smaller plates. The greater the charge (Q), the greater the capacitance (C) for a given applied voltage. Therefore, increasing the plate area of a capacitor increases its capacitance.

The spacing between the plates of a capacitor also determines the amount of charge that it can store. When you decrease the distance between the two conducting plates of a capacitor, the intensity of the field strength across the dielectric increases. As the field strength increases in intensity, the number of electrons that store on the negative plate, for a given applied voltage, increases. The greater this attraction, the greater the quantity of electrons stored in the capacitor, for a given applied voltage. In most capacitors, the distance between the two plates is a function of the thickness of the dielectric material that is used to manufacture the capacitor. When you move the plates closer together, you increase the capacitance. Likewise, when you move the plates farther apart, you decrease the capacitance.

The type of insulating material between the two plates of the capacitor also has an important effect on the amount of charge that a capacitor can store. Generally, the better the insulator that the dielectric is, the greater the capacitance. Many different types of insulating materials are used as a dielectric in capacitors. Insulators such as air, oil, paper, glass, and various types of plastics are widely used. Each type of insulator has a specific dielectric constant (K) that affects the amount of charge that a capacitor stores for a given applied voltage. Table 3-3 shows the dielectric constants for typical insulating materials.

Table 3-3

Dielectric Constants

MATERIAL	DIELECTRIC CONSTANT (K)
Air	1
Paper	3.5
Mica	6
Glass	6 to 10

The following formula shows the relationship between the factors that affect the capacitance of a capacitor. C is the capacitance in picofarads, A is the plate area in square inches, D is the distance between the plates in inches, and K is the dielectric constant of the dielectric material, and the value 0.2248 is the absolute dielectric constant of air or vacuum—also known as the absolute permittivity. If you know all of these factors, you can compute the capacitance as follows:

$$C = \frac{0.2248AK}{D}$$

As you can see by the formula, capacitance is directly proportional to plate area and the dielectric constant, and inversely proportional to the distance that separates the plates.

Example: What is the capacitance of a paper capacitor with a plate area of 18 square inches and a spacing of .005 inches?

$$C = \frac{0.2248(18)(3.5)}{0.005} = 2832.5 \text{ pF}$$

If A and D are given in the Metric System (centimeters), you need to use 0.0885 as the absolute permittivity constant to obtain the correct answer. That is, substitute 0.0885 for the 0.2248 absolute permittivity constant that is used in the English System (inches). Remember, both 0.2248 and 0.0885 arc conversion factors in the formula for capacitance.

Types of Capacitors

The two basic types of capacitors used in electronic circuits are fixed capacitors and variable capacitors. A fixed capacitor has a constant capacitance, and its physical construction is such that the capacitance remains at the same value under all conditions. A variable capacitor is designed so that its capacitance is adjustable.

Another method of classifying capacitors is by the type of dielectric used. The most commonly used dielectric materials are mica, ceramic, paper, and plastic films such as Mylar*. Oil is also used as a dielectric in some large capacitors for high-power applications. Another type of capacitor that is widely used in electronic applications is the electrolytic capacitor. Electrolytic capacitors have aluminum plates where the dielectric is a thin layer of aluminum oxide that is deposited on the plates during the manufacturing process. The dielectric is formed by an electro-chemical process right on the plates so that plate spacing is extremely small. This permits very high values of capacitance to be contained within a relatively small package.

Capacitors can be either polarized or nonpolarized. Electrolytic capacitors are polarized capacitors which means they have a definite polarity and you must observe this polarity when you install the electrolytic capacitor into a circuit.

* DuPont registered trademark.

If you install a polarized capacitor incorrectly (reversed in the circuit) it may short, become excessively hot, or even explode. The capacitor's positive or negative plate may be marked with a + or – sign and have an arrow pointing to the lead it refers to. The plus (+) side of the capacitor must be connected to the most positive potential. Likewise, the negative lead of the polarized capacitor must be connected to the most negative potential. An improperly installed polarized capacitor can cause bodily harm (when it explodes) or destroy components and entire circuit boards when it shorts or overheats. All polarized capacitors have the polarity markings stamped on their bodies.

Various fixed value capacitors have been developed to meet the wide range of electronic applications. For example, mica and ceramic capacitors are excellent for very high-frequency applications. Paper and plastic film capacitors are used in lower-frequency applications where higher values of capacitance are required. Figure 3-5 shows several types of fixed capacitors that are used in electronic circuits.

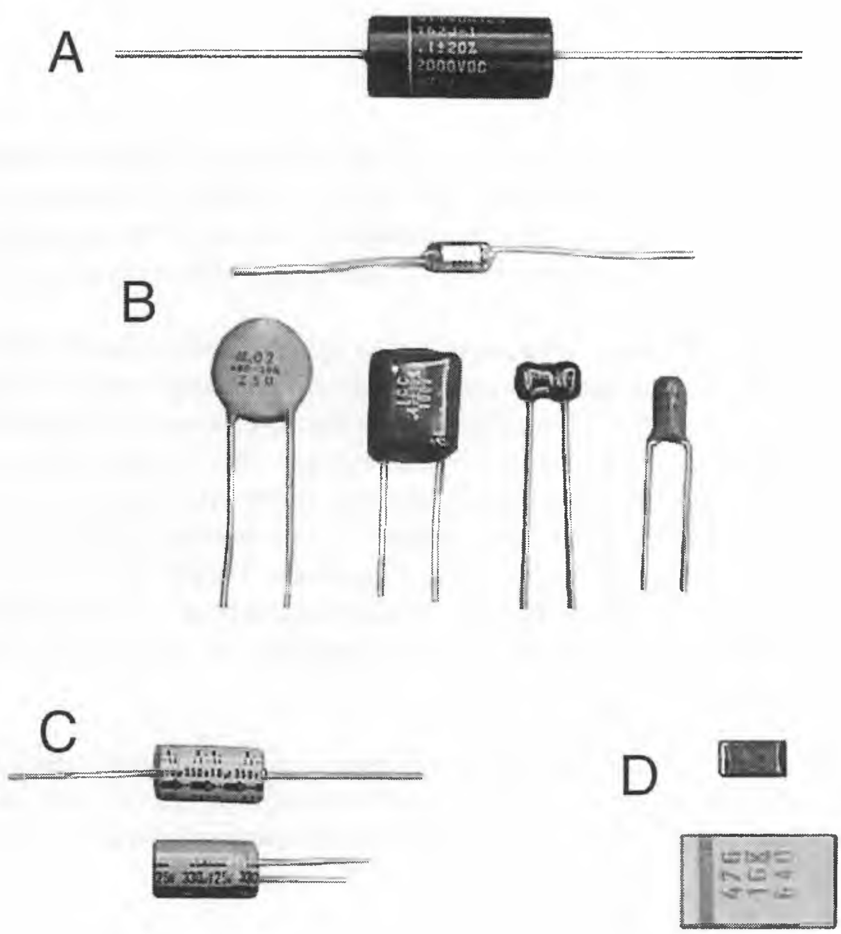


Figure 3-5

Typical fixed capacitors.
(A) paper. (B) Top: polystyrene. Bottom, left-to-right: ceramic, Mylar, mica, tantalum. (C) Two types of electrolytic.
(D) Two sizes of surface-mount (chip) capacitors.

Most variable capacitors have an air dielectric and are therefore referred to as air capacitors. Figure 3-6 shows a typical variable capacitor. Note the fixed plates (stator) and the variable plates (rotor). The capacitance increases as you rotate the variable plates to mesh with the fixed plates. Maximum capacitance occurs with full mesh and minimum capacitance occurs when the plates are not over lapped.

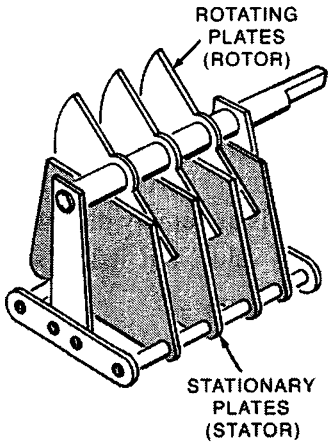


Figure 3-6
The variable capacitor.

Another type of variable capacitor called a trimmer uses a mica dielectric to obtain a relatively high value of capacitance in a small size. Trimmer capacitors with a ceramic dielectric are also available. Figure 3 7 shows the symbol that represents a variable capacitor in a schematic diagram. Trimmer capacitors are used to adjust the higher frequencies in a band of frequencies.

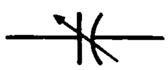


Figure 3-7
The schematic symbol
for a variable capacitor.

One old phrase that was widely used in the audio communication field was to trim them on the top and pad them on the bottom, when a piece of equipment contained capacitors to adjust (balance) the gain over a range of frequencies. Trimmer capacitors adjust the high frequencies and padder capacitors adjust the lower end of the frequency band. When they are properly adjusted, the gain is relatively stable across the frequency band.

Capacitor Ratings

All capacitors are rated according to two basic characteristics: capacitance and working voltage. Capacitors come in a variety of standard capacitance values. Standard ranges cover from as high as several thousand microfarads to as low as one picofarad. Working voltage is listed as a DC voltage.

Another capacitor characteristic is its voltage rating. All capacitors are designed to be able to withstand an applied voltage of a certain maximum value. This voltage rating is a function of the type of dielectric and its thickness. If you exceed the voltage rating of a capacitor, it is possible to rupture the dielectric and cause the plates of the capacitor to short together. In some very high value capacitors, the dielectric material is extremely thin. A very thin dielectric is responsible for the high capacitance value, but it is also easier to puncture the thin dielectric with high voltage.

Capacitors are generally rated in terms of an operating or working voltage. This is the maximum voltage that you can safely applied to the capacitor on a continuous basis. For example, a capacitor with a 200-volt rating can operate continuously with any value of DC voltage less than 200 volts. A voltage greater than 200 volts may cause damage to the capacitor. On the other hand, a 200-volt capacitor operates quite satisfactorily at 50-volts DC. You will often see working voltage abbreviated WV.

Another capacitor voltage rating is peak voltage. The peak voltage is the maximum voltage that a capacitor can withstand when it is used with an AC voltage. For example, assume that a capacitor has a peak voltage rating of 1000 volts. This means the peak AC value applied to the capacitor must never exceed 1000 volts. If you apply a 1000-volt rms sine wave to the capacitor, you have exceeded its voltage rating, and the capacitor may become damaged. The peak value of a 1000-volt rms sine wave is 1000 divided by 0.707 or 1410 volts. This of course exceeds the peak voltage rating.

You must consider both the capacitance and voltage ratings of a capacitor in terms of their tolerance ratings. It is extremely difficult and expensive to design components which have capacitance and voltage ratings exactly as specified. Therefore, most practical electronic components have a tolerance range on their ratings. A typical capacitance value might have a tolerance of plus and minus 10 % (+10 %). This means that the actual value of the capacitor could be 10% higher or 10% lower than the actual rated value. While 10% is a typical capacitance tolerance, capacitors with wider tolerance ranges and narrower ranges are also available. For example, one percent tolerance capacitors are available. However, closer tolerances are more expensive, this is partly due to the additional

expense to make, but just as important is that the number of applications for the component is reduced. Therefore, precision components are manufactured in smaller quantities than standard components. Some very large capacitors have tolerances as great as 80%.

Tolerances on voltage ratings are generally undefined and very broad. The voltage ratings of a capacitor are also very conservative so that the actual voltage rating is generally much higher than the stated working value. While this is true, it is still poor practice to use a capacitor in a circuit where the voltage exceeds its rated value, despite the fact that its actual capability might be higher.

Capacitor Defects

Like any electronic component, capacitors are subject to defects. Defects may occur in the manufacturing process or may be caused by an improper electrical condition in the circuits in which they are used. There are four common ways that capacitors fail. A capacitor can become shorted or open. The capacitor can have excess leakage or it can change in value.

In a shorted capacitor, the plates either touch or a very low resistance path forms between the plates. Internal shorts usually occur when the dielectric becomes punctured or otherwise fails. A shorted capacitor has a very low resistance and can often cause damage to other components in the circuit.

An open capacitor occurs when one or possibly both of the leads become disconnected from the plates. An open capacitor has a very high resistance and causes an open in the circuit.

A capacitor with excessive leakage occurs when a resistive path is forms between the two plates. A good capacitor should be an open circuit to direct current (capacitors block DC currents) and should measure infinite (or extremely high) resistance between the two leads. However, a lower resistance sometimes occurs when the dielectric fails. The resistance that develops between the two plates is referred to as leakage resistance. It has the effect of an external resistor connected across the capacitor's leads. You can sometimes detect leakage by measuring the capacitor with an ohmmeter. When an ohmmeter is connected across a capacitor, the meter indication constantly increases as the capacitor charges to the ohmmeter's internal voltage source. When the capacitor is fully charged, the meter reading becomes stable. If the meter indication starts decreasing or the indication fluctuates, the capacitor is charging and discharging. This is a indication of changing internal capacitor resistance and is referred to as leakage.

Capacitors can also change in value. A fixed capacitor has a specific given value, but when it is used in a circuit, the capacitor may no longer have that specific value of capacitance. The capacitance value can change due to an incorrect applied voltage, excessive temperature conditions, or as in the case of electrolytic capacitors, expired shelf life. Electrolytic capacitors actually hold their values better when they are used in circuits than they do on the shelf.

Capacitors in Series and Parallel

Capacitors are often connected in series or parallel to form new values of capacitance. When two or more capacitors are connected in series or parallel, the capacitance of the combination is greater than or less than the values of the individual capacitors. Because such combinations occur so frequently in electronic circuits, it is desirable to know how to compute the total capacitance of the various combinations. The following simple procedures show you how to do this.

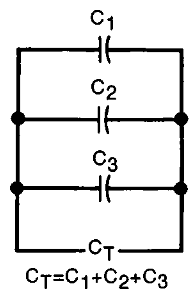


Figure 3-8
Capacitors connected in parallel.

CAPACITORS IN PARALLEL

When two or more capacitors are connected in parallel as shown in Figure 3-8, the total capacitance of the combination is simply equal to the sum of the individual capacitances. If the total capacitance of the combination is designated C_T, the total capacitance is the sum of the individual capacitors as indicated by the expression:

$$C_T = C_1 + C_2 + C_3$$

For example, if C1 = .015 µF, C2 = .002 µF, and C3 = 10()0 pF, the total sum of the combination is:

$$C_T = .015\ \mu F + .002\ \mu F + .001\ \mu F = .018\ \mu F.$$

In a parallel circuit configuration, total capacitance is always greater than any single value in the combination. Remember, capacitors in parallel add like resistors in a series circuit.

The most important thing to note, when you make capacitance calculations such as this, is that all values of capacitance must be expressed in the same units. In this example, C_1 and C_2 arc given in μF, but C_3 is expressed in pF. In order to make the proper calculation, all values were changed to μF. A 1000 pF capacitor is the same as a .001 μF capacitor. Remember, to convert pF to μF, you divide the capacitance value in pF by 1,000,000 (10^6)

CAPACITORS IN SERIES

When two or more capacitors are connected in series as shown in Figure 3-9, the total capacitance of the combination is less than the capacitance of the smaller capacitor in the combination. This is the same relationship that applies to resistors connected in parallel.

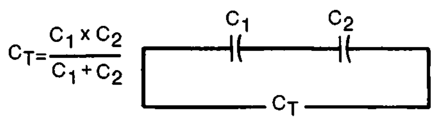


Figure 3-9
Capacitors in series.

The formula for calculating total capacitance, C_T, of two capacitors connected in series is:

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

For example, assume that two capacitors, C_1 = .001 μF and C_2 = 390 pF, are connected in series. The total capacitance is:

$$C_T = \frac{1000 \times 390}{1000 + 390} = \frac{390000}{1390} = 280.6 \text{ pF}$$

Note that C_1 is expressed in μF while C_2 is expressed in pF. In order to compute the proper value of capacitance, the values of both capacitors must be expressed in the same units. Here, both are expressed in picofarads. A .001 μF capacitor is equal to 1000 pF. Note that the total capacitance of the combination is less than the smallest capacitor's value.

When more than two capacitors are connected in series, you can use the above formula to compute the total by combining the capacitors two at a time. For example, in a circuit with three capacitors in series, you first compute the combination capacitance of two of them. Then, you combine this combination capacitance with the third value of capacitor in the same formula to arrive at the correct total. This method is the same as the product over the sum formula you use for paralleled resistors. The reciprocal method that you use for resistors in parallel also applies to capacitors in series.

Capacitors in DC Circuits

When you use capacitors in circuits that involve DC voltages, they exhibit certain properties and operational characteristics. In AC circuits, capacitors have different properties and characteristics. Since capacitors are usually considered to be AC components, most of this unit is devoted to the operation of capacitors in AC circuits. However, many AC circuits also use DC voltages. For that reason, you will first study the operation of capacitors in DC circuits.

Since there is no direct electrical connection between the plates of a capacitor, a capacitor represents essentially an open circuit (infinite resistance) to a DC voltage. There is no direct path for electrons to flow through the capacitor. However, when a capacitor charges or discharges, movement of electrons takes place within the circuit. This movement of electrons constitutes current flow, but this charging or discharging action is transient (short-time duration) in nature. Once the capacitor has charged or discharged, current ceases to flow. While electrons do not cross between the plates of a capacitor, the charging and discharging action does cause movement of electrons in the external circuit. If a component (such as a resistor) is connected in series with the capacitor, it will have a voltage drop developed across it as the capacitor charges and discharges. The voltage dropped across the resistor reverses polarities due to current moving in one direction during charging and moving in the opposite direction during the discharge cycle.

Figure 3-10 shows a simple series resistor-capacitor (RC) circuit connected to a DC voltage source. With the switch open and the capacitor initially discharged, no current flows in the circuit. However, when you close the switch, the capacitor starts to charge. Electrons from the negative terminal of the battery flow through the switch and the resistor to the right-hand plate of the capacitor. Electrons are drawn from the left hand plate of the capacitor by the positive terminal of the battery, which leaves the left plate positively charged. Once the capacitor is fully charged, current flow ceases. During the charging time, electrons flow through resistor (R) in the direction shown. This results in a voltage drop across the resis-

tance with the polarity as indicated. This voltage appears only momentarily as the capacitor charges. When the switch is initially closed, electrons begin to flow immediately and a peak voltage appears across the resistor. As the capacitor charges, the voltage drop across the resistance decreases. The voltage across the resistor is zero when the capacitor is fully charged or completely discharged.

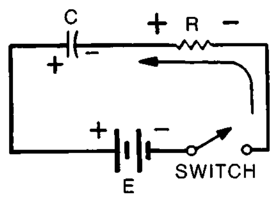


Figure 3-10
A series RC circuit.

The series combination of resistance and capacitance shown in Figure 3-10 is a common configuration. There are many variations and applications for this simple circuit. The most important characteristic of this RC combination is the time it takes to charge or discharge the capacitor. This time is referred to as the time constant, T. The time constant is the period of time it takes for a capacitor to charge to approximately 63.2% of the applied voltage. This time is the product of the circuit's resistance and capacitance value:

$$T = RC$$

The time constant in seconds is equal to the capacitance in farads, multiplied by the resistance in ohms. One time constant in seconds is also equal to the resistance in megohms multiplied by the capacitance in microfarads. For example: What is the time constant of a 25 μF capacitor and a .47 megohm resistor? The applied voltage is 12 volts.

$$T = 25\ (10^{-6}) \times .47\ (10^{6}) \text{ or } 11.75 \text{ seconds}$$

In other words, it takes the 25 μF capacitor 11.75 seconds to charge to 63.2% of 12 ($.632 \times 12 = 7.584$) or 7.584 volts through a .47 megohm resistor.

After one time constant, the voltage across a capacitor is equal to 63.2% of the applied voltage. It takes approximately five time constants for the capacitor to charge to the full applied voltage. In the above example, it takes $5 \times 11.75 = 58.75$ seconds for the capacitor to charge to 12 volts.

The time constant relationship also holds true when a capacitor discharges. See Figure 3-11. A capacitor is initially charged to an applied voltage, when you close the switch. When you open the switch, the capacitor discharges through the resistor. The time constant (T), is the time it takes the capacitor to discharge to 36.8% of the initial voltage. This is another way of saying that in one time constant, the capacitor's charge decreases by 63.2%. It takes approximately five time constants for the capacitor to discharge completely. If the capacitor is initially charged to 36 volts, after one time constant its voltage is 36 × .368 = 13.25 volts.

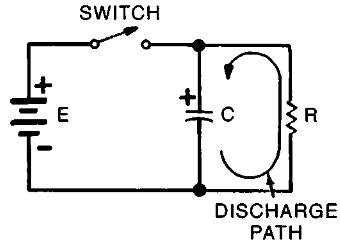


Figure 3-11

A parallel RC circuit.

For each time constant, the capacitor changes it charge by 63.2%. As you can see, if the capacitor changes its charge by 63.2% each time constant, the capacitor never fully charges to the applied voltage or never fully discharges to zero. However, after 5 time constants the charge is so close to either the supply voltage or zero that it is appropriate to assume the capacitor changed its charge by 100%.

For example, assume that a capacitor is charging to 100 volts.

After 1 time constant the charge is 63.2 volts.

100 V – 63.2 V = 36.8 V.

After 2 time constants
(.632 × 36.8 V) + 63.2 volts.

23.26 V + 63.2 V = 86.46 V.

After 3 time constants
(.632 × 13.54 V) + 86.46 volts.

8.56 V + 86.46 V = 95.02 V.

After 4 time constants
(.632 × 4.98 V) + 95.02 volts.

3.15 V + 95.02 V = 98.17 V.

After 5 time constants
(.632 × 1.83 V) + 98.17 volts.

1.16 V + 98.17 V = 99.33 V.

Since there are tolerances in all electronic circuits, you can assume 99.33% or 5 time constants is close enough to call it 100%.

Programmed Review

1.	A capacitor is an electronic component that is made up of two conducting plates which are separated by an insulating medium called the ___________.
2.	(dielectric) Because the dielectric is an insulator, no current can flow through the capacitor. This means that no ___________ pass through the dielectric from one plate to the other.
3.	(electrons) When you apply a DC voltage to a capacitor, electrons build up on one plate and are drawn from the other. In this state, the capacitor is said to be ___________.
4.	(charged) The charges on the plates attract one another across the dielectric to create an electric field. If you remove the DC voltage, the charge remains. The charge is said to be ___________ in the capacitor.
5.	(stored) To release and use the charge stored in the capacitor, you can connect the plates together externally. When this happens, the capacitor ___________.
6.	(discharges) Electrons on the negative plate flow to the positive plate and neutralize the charge. The only time that current flows in a capacitive circuit is when the capacitor is ___________ or ___________.
7.	(charging, discharging) When electrons move in the circuit, current flows. But, no electrons pass between the plates of the capacitor because the dielectric is an ___________.
8.	(insulator) The capacitor in a circuit does not have to be a packaged capacitor. Instead, it can take the form of any two conductors separated by an insulator. Such capacitance is called ___________ capacitance.

9.	(distributed or stray) The unit of capacitance is the __________.
10.	(farad) This unit tells you the amount of charge in coulombs that a capacitor can store for a given applied voltage. The farad is a very large unit. Most practical capacitors are rated in smaller units such as __________ or __________.
11.	(microfarads, picofarads). The abbreviations for these units are __________ and __________ respectively.
12.	(μF, pF) A microfarad is one millionth of a farad. A picofarad is one millionth of a microfarad. This means that there are __________ (how many?) μF in a farad.
13.	(1,000,000) There are __________ pF in one microfarad.
14.	(1,000,000) It is often necessary to convert from one unit of capacitance to another. For example, 2200 pF expressed in μF is __________.
15.	(.0022) You multiply pF by 10^{-6} to get μF. $2200 \times 10^{-6} = 2200 \times .000001 = .0022$ μF. A value of .47 μF is equivalent to __________ pF.
16.	(470,000) You multiply μF by 10^{6} or 1,000,000 to get pF. $.47 \times 1{,}000{,}000 = 470{,}000$ pF. The capacitance of a given capacitor is a function of its physical characteristics. The three basic factors that affect capacitance are __________, __________, and __________.
17.	(plate area, plate spacing, dielectric constant.) The capacitance is directly proportional to the area of the plates. This means the larger the plate area, the __________ the capacitance.

18. (greater) The capacitance is also directly proportional to dielectric constant. This constant is different for different types of capacitors. The better the insulating capabilities, the greater the dielectric constant. When the dielectric constant decreases, the capacitance ____________.

19. (decreases) The spacing between the plates also affects the capacitance. Capacitance is inversely proportional to the distance between the plates. When you decrease the separation, the capacitance ____________.

20. (increases) There are two basic classifications of capacitors. These are ____________ and ____________.

21. (fixed, variable) Fixed capacitors have a constant value and come in a variety of shapes and sizes. They are usually classified according to the type of ____________ used in them.

22. (dielectric) Typical electronic capacitors have dielectrics of mica, ceramic, paper, and plastic. A special type of fixed capacitor that has an aluminum oxide dielectric is called an ____________.

23. (electrolytic) Variable capacitors are made so you can vary their capacitance over a narrow range. Most variable capacitors have an ________ dielectric.

24. (air) Variable capacitors called trimmers are available with mica and ceramic dielectrics. The dielectric constant of mica or ceramic is ____________ than that of air.

25. (greater) Capacitors are also rated by applied voltage. A capacitor with a working voltage of 100 volts can withstand a DC operating voltage of anything less than ________ volts.

26. (100) A capacitor may be damaged with an applied voltage that exceeds the working voltage rating. Another voltage rating is the peak value. The peak value refers to the maximum _________ voltage that a capacitor can withstand.

27. (AC) The peak value refers to the maximum allowable peak AC value that the capacitor can handle. If the applied voltage exceeds the rated value, the capacitor can become damaged. For example, the dielectric can rupture and the plates can touch which causes a __________.

28. (short) Alternately, the punctured dielectric can act as a resistance rather than a dielectric short. This resistance is referred to as __________.

29. (leakage) Another typical capacitor defect is lead breakage. This creates a condition known as an _________ capacitor.

30. (open) Finally, a capacitor can change in value under operating conditions. Two factors that can cause this are excessive __________ or __________.

31. (voltage, temperature) Capacitors are often connected in series or parallel to form different values of capacitance. In a parallel combination, the total capacitance is always __________ than any of the individual capacitors.

32. (greater) The total capacitance of parallel capacitors is the sum of the individual capacitors. The total capacitance of a 680 pF and a 750 pF capacitor in parallel is _________ pF.

33. (1430 pF) In microfarads, this value is __________.

34. (.00143μF) To convert pF to μF, divide by 1,000,000 or 1430 ÷ 1,000,000 = .00143. When capacitors are connected in series, the total capacitance is always _________ than the smaller capacitance.

35. (less) The formula for finding the total capacitance of two capacitors in series is ___________ .

36. ($C_T = \frac{C_1C_2}{C_1 + C_2}$) If C_1 is .0015 μF and C_2 is 560 pF, the total capacitance is ___________ .

37. (.0004078 μF) To solve this problem, both capacitor values must be expressed in the same units, in this case, μF. C_1 is already in μF, but you must convert C_2. Therefore 560 pF = 560 × .000001 = .00056 μF and

$$C_T = \frac{.0015 \times .00056}{.0015 + .00056} = \frac{.00000084}{.00206} = .000407\ \mu F$$

This value in pF is _________ .

38. (407.8) When a capacitor is connected in series with a resistor and a DC voltage source, the capacitor ___________ .

39. (charges) The voltage across the capacitor rises toward the applied DC voltage. The time that is required for the voltage across the capacitor to increase to 63.2% of the applied voltage is called the _________ ___________ .

40. (time constant) It takes a specific amount of time for the capacitor to charge to the applied voltage. This time is determined by the values of and ___________ and ___________ in the circuit.

41. (resistance, capacitance) The time constant is directly proportional to values of resistance and capacitance. If either R or C increases, the time constant ___________ .

42. (increases) If you decrease R or C, the __________ ____________ decreases.

43. (time constant) The time constant (T) is computed with the expression $T = RC$. If $R = 1.2$ megohms and $C = .68\ \mu F$, the time that it takes the capacitor to charge to 63.2% of the applied voltage is __________ seconds.

44. (.816) This is equivalent to 816 milliseconds or a little more than eight tenths of a second. It takes about __________ seconds for the capacitor to charge to the full applied voltage.

45. (4.08) It takes five time constants for the capacitor to charge to the applied voltage. In this example, it is $5 \times .816$ or 4.08 seconds. If the applied voltage is 20 volts, the charge on the capacitor will be __________ volts after .816 seconds.

46. (12.64) After one time constant, the capacitor charges to 63.2% of 20 volts or $.632 \times 20 = 12.64$ volts. The time constant also applies when the capacitor discharges. After one time constant, the voltage across the capacitor is __________ % of its initial charge.

47. (36.8) It takes five time constants for the capacitor to discharge.

CAPACITORS IN AC CIRCUITS

When an AC voltage is applied to a capacitor, alternating current flows in the circuit. Figure 3-12 shows a sine wave generator, E, connected to a capacitor, C. As the AC voltage varies, the current in the circuit follows a sinusoidal variation. Electrons do not pass directly through the dielectric, from one plate of the capacitor to the other. Although electrons do not pass from one plate to the other through the dielectric, electrons do flow in the circuit external to the capacitor as if they do. As the applied AC voltage rises and then falls, the capacitor charges and then discharges. The frequency of the input voltage and the circuit's time constant determine the charge and discharge rate of the capacitor. Even though there isn't a physical resistor shown in Figure 3-12, all circuits contain a finite resistance. Also note that the arrow in Figure 3-12 indicates that current flows first in one direction and then reverses so it flows in the other direction. This oscillating current is also the definition of a sine wave.

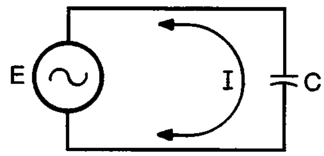


Figure 3-12
An AC voltage source connected to a capacitor.

Figure 3-13 illustrates the action of an electron in the dielectric of a capacitor. This illustration also shows the effect an applied AC voltage has on the atoms within the dielectric of a capacitor. In Figure 3-13A, the external applied voltage is zero. At this time, the electrons contained in the atoms of the dielectric rotate normally about their nuclei. Note what happens to the orbit of the electron, when the capacitor charges as shown in Figure 3-13B. Here, the upper plate is made negative with respect to the lower plate. The electrons that orbit the nucleus in the dielectric are repelled by the negative plate and attracted by the positive plate. This distorts the orbit of the electrons. The amount of voltage applied to the capacitor determines the amount of orbit distortion. Figure 3-13C shows the or bit distortion when the capacitor charges in the opposite direction.

When you apply a constantly changing AC voltage to the capacitor, the polarity of the applied voltage alternates to cause the electrons in the dielectric to change directions. While the amount of electron shift is small, it nevertheless constitutes a movement of electrons within the dielectric. While none of the electrons actu-

ally break loose from their orbits and flow in the external circuit, you can say that the movement of electrons constitutes current flow. As the AC voltage charges and discharges the capacitor, the movement of electrons onto one plate and off the other in the external circuit represents current flow. When the applied voltage is a sine wave, current flow in the circuit is also sinusoidal.

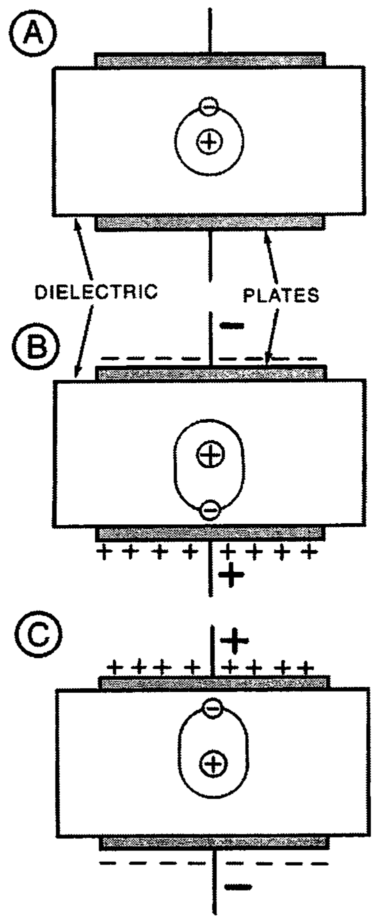


Figure 3-13
Electron distortion in the dielectric of a charged capacitor.

Current-Voltage Relationships in Capacitive AC Circuits

The relationship between current and applied voltage in a capacitive circuit is different than it is in purely resistive AC circuits. Due to the way that a capacitor functions, current and voltage in a capacitive AC circuit are not in phase with each other. In a circuit where an AC voltage is applied to a resistance, current through the resistor follows the voltage that is applied to it. In this case, current and voltage are in phase. In other words, the positive and negative half cycles of voltage and current in a resistive AC circuit are in step with one another.

In a capacitive AC circuit, the capacitor constantly charges and discharges at the rate of change of the applied voltage. Once the capacitor is initially charged, the voltage across it acts as a voltage source. Its effect is to oppose changes in the external supply voltage. Since the capacitor must charge or discharge to follow the changes in the applied voltage, the resulting current flow is out of step with the changes in the applied voltage. There is a phase shift between the voltage and current in the circuit. In a purely capacitive circuit, the phase shift is 90°, so the current leads the voltage by 90°.

To understand the relationship between current and voltage in a capacitive AC circuit, you should first review the basic principles of capacitor operation when a DC voltage is applied. Figure 3-14 shows a DC voltage source connected to a capacitor. The capacitor is initially discharged and the switch is open. When you close the switch, the instantaneous voltage across the capacitor is zero. It might appear that the voltage across the capacitor is initially equal to the applied voltage, the instant the switch is closed, but it is zero because electrons have not had time to flow to and from the plates of the capacitor. In other words, on the initial closure of the switch, the capacitor is still uncharged. Immediately thereafter, electrons begin to flow. Electrons flow from the negative terminal of the battery to the right-hand plate of the capacitor, which gives that plate an excess of electrons and a negative charge. At the same time, electrons are drawn from the left hand plate of the capacitor to the positive terminal of the battery, which causes the left-hand plate to have a positive charge. As electrons begin to flow, a voltage builds up across the capacitor. The polarity of voltage across the capacitor at this time is indicated in Figure 3-14. Note that this voltage is in direct opposition to the applied voltage. When the capacitor is fully charged to the applied voltage, the two voltages are equal in amplitude and opposite in polarity. The voltages therefore cancel each other, and the effective voltage in the circuit is zero. When the voltages are equal, there is no difference of potential and current ceases to flow.

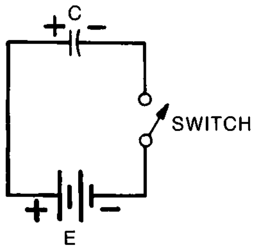


Figure 3-14
A capacitor being charged by a DC source.

Remember that according to Kirchhoff's Voltage Law, the sum of the voltages around a closed loop must equal zero.

Figure 3-15 illustrates the relationship between the capacitor's current and voltage in the circuit of Figure 3-14. When the switch is initially closed, the capacitor voltage is zero while the current in the circuit is maximum. As the electron flow charges the capacitor, the capacitor voltage begins to build up. The capacitor voltage opposes the applied voltage, which reduces the amount of current flow in the circuit. When the capacitor becomes fully charged, the current in the circuit reduces to zero.

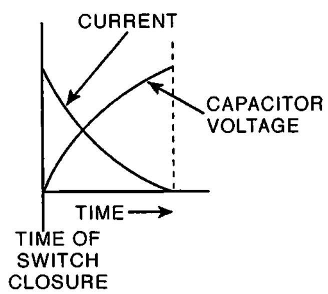


Figure 3-15
Relationship between voltage and current in a charging capacitor.

Now, you can use the relationship shown in Figure 3-15 to show the actual current and voltage relationships in a capacitive circuit when an AC signal is applied. Once the capacitor becomes charged, the voltage across the capacitor is the same as the applied voltage. However, the current flowing in the circuit is out of phase with the voltage as indicated in Figure 3-15.

The exact relationship between the current and voltage in a capacitive circuit when a sine wave is applied is shown in Figure 3-16. Note that when the current is maximum, the voltage across the capacitor is zero. As you can see, there is a phase shift between the current and voltage in the circuit. This phase shift is expressed in terms of degrees. Remember that one complete cycle of an AC sine wave contains 360°. The amount of phase shift in the capacitive circuit is one fourth of this or 90°. The current and voltage in a purely capacitive circuit are 90° out of phase with one another. Another important fact to note is that the change in current leads the change in voltage. As Figure 3-16 shows, the capacitor voltage change follows the current change in time. The cur rent leads the voltage in a capacitive circuit; there is a 90° leading phase shift in a purely capacitive circuit.

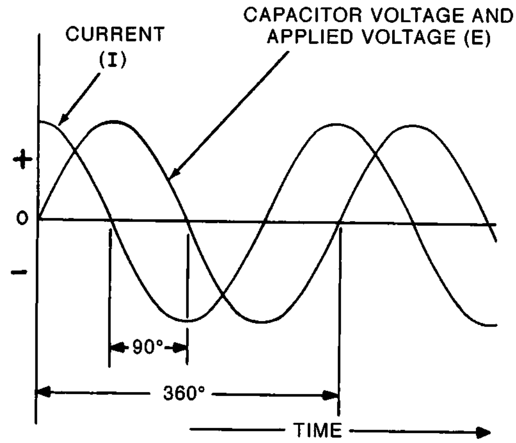


Figure 3-16
Current and voltage relationship in a purely capacitive AC circuit.

Capacitive Reactance

It is the basic nature of a capacitor to oppose changes in voltage. In a DC circuit, a capacitor charges to the applied voltage. If you increase the applied voltage, the capacitor then charges to the new higher voltage. If you decrease the applied voltage, the capacitor discharges until the voltage across it equals the new lower applied voltage. Keep in mind that it takes a finite period of time for a capacitor to charge or discharge to a new voltage level. The charge and discharge time is a function of the capacitor's size and the value of any series resistance in the circuit.

In an AC circuit, the capacitor constantly charges and discharges. The voltage across the capacitor is in constant opposition to the applied voltage. This constant opposition to changes in the applied voltage creates an opposition to current flow

in the circuit. This opposition to AC current flow by a capacitor is called capacitive reactance. Capacitive reactance is represented by the symbol X_C and, like resistance, it is measured in ohms.

The capacitive reactance of a capacitor is determined by its capacitance value and the frequency of the applied voltage. The amount of opposition to current flow in an AC circuit by a capacitor is a function of the capacitance and the frequency of the AC voltage. Capacitive reactance is inversely proportional to capacitance and frequency. Therefore, when you increase the capacitance or frequency, the capacitive reactance decreases.

The capacitive reactance is calculated by using the equation:

$$X_C = \frac{1}{2\pi fC}$$

In this expression, X_C is the capacitive reactance in ohms, f is the frequency in Hz, C is the capacitance in farads and pi (π) is a constant that is approximately 3.14. Since $1/2\ \pi = 1/6.28 = .1592$, you can simplify the expression as shown below:

$$X_C = \frac{.1592}{fC}$$

Since farads is an unrealistically large unit of capacitance, this formula is difficult to use. If you assume that the capacitance in the formula is expressed in microfarads, the expression for capacitive reactance becomes:

$$X_C = \frac{159200}{fC}$$

The following examples show how to compute capacitive reactance when you know the frequency of operation and the capacitance. These examples illustrate the effect of frequency and capacitance on the reactance.

1. What is the reactance of a 1 microfarad capacitor at 60 Hz?

$$X_C = \frac{159200}{60(1)} = \frac{159200}{60} = 2653 \text{ ohms}$$

2. If you increase the frequency to 120 Hz, what is the new value of reactance of the 1 microfarad capacitor?

$$X_C = \frac{159200}{120(1)} = \frac{159200}{60} = 1326 \text{ ohms}$$

When the frequency increases, the reactance decreases by one half.

3. What is the reactance of a 1000 pF capacitor at 2 kHz?

1000 pF = .001 μF

2 kHz = 2000 Hz

$$X_C = \frac{159200}{2000(.001)} = 79600 \text{ ohms or } 79.6 \text{ k ohms}$$

4. If you decrease the capacitance from 1000 pF to 500 pF, what is the reactance at 2 kHz?

500 pF = .0005 μF

$$X_C = \frac{159200}{2000(.0005)} = 159{,}200 \text{ ohms or } 159.2 \text{ k ohms}$$

When you halve the capacitance, the reactance doubles.

These examples show you how to compute the reactance when you know the frequency and the capacitance. It is often necessary to compute the frequency when you know the reactance and capacitance, or to compute the capacitance when you know the reactance and frequency. The formulas for these calculations are:

$$f = \frac{159200}{X_C C}$$

$$C = \frac{159200}{f X_C}$$

Where:

f = frequency in Hz
C = capacitance in μF (10^{-6})
X_C = capacitive reactance in ohms.

Examples:

1. At what frequency will a .039 μF capacitor have a reactance of 7000 ohms?

$$C = \frac{159200}{7000(.039)} = 583.1 \text{ Hz}$$

2. What value of capacitance has a reactance of 23 k ohms at a frequency of 2 MHz.

$$23\ k\Omega = 23{,}000 \text{ ohms}$$

$$2 \text{ MHz} = 2{,}000{,}000 \text{ Hz}$$

$$C = \frac{159200}{23000(2000000)} = .0000034\ \mu F$$

$$C = .0000034 \times 10^6 = 3.4 \text{ pF}$$

Ohm's Law in Capacitive Circuits

Ohm's Law describes the basic relationship between the current, voltage, and resistance (opposition) to current flow in an electrical circuit. Because of its capacitive reactance in an AC circuit, a capacitor is just as effective as a resistor in controlling current flow.

Since a purely capacitive circuit has capacitance but no resistance, the current is directly proportional to the applied voltage, and inversely proportional to the capacitive reactance. This relationship is shown in the formula below:

$$I = \frac{E}{X_C}$$

For example, assume that an AC voltage of 6.3 volts is applied to a capacitor with a reactance of 210 ohms. The current in the circuit is:

$$I = \frac{E}{X_C} = \frac{6.3}{210} = .03 \text{ amperes or 30 milliamperes}$$

You can rearrange the basic Ohm's Law formula to compute the voltage and reactance:

$$E = IX_C$$

$$X_C = \frac{E}{I}$$

The following examples illustrate Ohm's Law in these cases.

1. A .05 μF capacitor has a current of .1 ampere at 400 Hz. What is the voltage across it?

$$X_C = \frac{159200}{fC} = \frac{159200}{400(.05)} = 7960 \text{ ohms}$$

$$E = IX_C = .1(7960) = 796 \text{ volts}$$

2. A capacitor has 200 volts of 60 Hz AC across it and a current of .02 amperes. What is the value of capacitance?

$$X_C = \frac{E}{I} = \frac{200}{.02} = 10{,}000 \text{ ohms}$$

$$C = \frac{159200}{fX_C} = \frac{159200}{60(10000)} = .256\ \mu\text{F}$$

Programmed Review

48. When you apply an AC voltage to a capacitor, current will flow. Electrons do not flow between the capacitor plates across the dielectric, but they do flow onto and off of the ___________ as the AC voltage rises, falls, and changes polarity.

49. (plates) Electrons pile up on one plate and are drawn from the other on one-half cycle of the applied AC. When the polarity of the AC voltage reverses, the charge on the capacitor reverses. In other words, as the AC voltage varies, the capacitor ___________ and ___________.

50. (charges, discharges) The capacitor charges first in one direction, then discharges and recharges in the opposite direction. The constant charging and discharging keeps the electrons moving. Therefore, current flows in a capacitive circuit even though no electrons pass through the capacitor ___________.

51. (dielectric) Because it takes time for the capacitor to charge and discharge, the current does not flow in step with the applied voltage. Therefore, the current and voltage are out of ___________.

52. (phase) In an AC circuit with only resistance, the current is in step or in phase with the applied voltage. The maximum, minimum, and zero points are the same for the voltage and current. In a capacitive circuit the current ___________ the voltage.

53. (leads) When the current is maximum, the voltage is zero. When the voltage is zero, the current is ___________.

54. (maximum) With a sine-wave voltage, this puts the current 90° out of phase with the voltage. The current and voltage are shifted in time from one another by one quarter of a cycle or ___________ degrees.

55. (90) The current leads the voltage by 90°. Another way of saying this is that the voltage ___________ the current.

56. (lags) If the current leads the voltage, then the voltage lags the current. When a capacitor charges, it stores a voltage. A charged capacitor then acts as a ___________ ___________.

57. (voltage source) A charged capacitor can create current flow. The voltage across a capacitor also opposes the applied voltage that caused it to become charged in the first place. Both the applied voltage and the charge on the capacitor determine the amount of ___________ in the circuit.

58. (current) The effective circuit voltage is a function of the difference between the applied voltage and the charge on the capacitor. Since the charge opposes the applied voltage, this has the effect of ___________ the current in the circuit.

59. (decreasing) The opposition to AC by a capacitor is called the ___________ ___________.

60. (capacitive reactance) It is represented by the symbol X_C. The unit of capacitive reactance is the ___________.

61. (ohm) Like resistance, capacitive reactance is an opposition to current flow. Therefore, you use the ohm to express the amount of opposition. The amount of capacitive reactance in a circuit is determined by the ___________ and ___________.

62. (frequency, capacitance) The frequency of the applied voltage and the capacitance affect the reactance. The reactance is ___________ proportional to frequency and capacitance.

63. (inversely) This means that when you increase either the frequency or capacitance, this causes the reactance to ___________.

64. (decrease) To increase the reactance, you must ___________ the capacitance or frequency.

65. (decrease) You can use the following formula to compute the capacitive reactance:

$$X_C = \frac{159200}{fC}$$

Where:

X_C is in ohms
f is in Hz
C is in µF

The reactance of a .0047 µF capacitor at 1500 Hz is ___________ ohms.

66. (22581) The solution is:

$$X_C = \frac{159200}{1500(.0047)} = \frac{159200}{7.05} = 22581$$

To decrease this reactance you have to ___________ frequency or ___________ the capacitance.

67. (increase, increase) The current (I) in a capacitive circuit is directly proportional to the applied voltage (E) and inversely proportional to the reactance (Xc). This is expressed by the Ohm's Law formula __________.

68. ($I = \frac{E}{X_C}$) The current in a .068 µF capacitor at 800 Hz with 5 volts applied is ___________.

69. (1.71 milliamperes) You first compute the reactance:

$$X_C = \frac{159200}{fC} = \frac{159200}{800(.068)} = \frac{159200}{54.4} = 2926.5 \text{ ohms}$$

Then the current:

$$I = \frac{E}{X_C} = \frac{5}{2926.5} = .00171 \text{ amperes or } 1.71 \text{ milliamperes}$$

To increase the current in a circuit, you must ____________ the reactance.

70. (decrease) To decrease the current in a circuit, you can ____________ the frequency or the capacitance.

71. (decrease) When you decrease C or f, X_C increases and the current decreases. A capacitor has a voltage drop of 70 volts at 60 Hz and the current is .08 amperes. The value of the capacitance is __________ µF.

72. (3.03) Since you know the voltage and current, you first compute the reactance:

$$X_C = \frac{E}{I} = \frac{70}{.08} = 875 \text{ ohms}$$

Since you now know the reactance and frequency, you can compute the capacitance:

$$C = \frac{159200}{fX_C} = \frac{159200}{60(875)} = \frac{159200}{52500} = 3.03\ \mu F$$

RC CIRCUITS

While purely capacitive circuits are sometimes used in electronics, more often capacitors are combined with other components to form electronic circuits. The most common circuits contain a resistor and capacitor connected in series. Despite its simplicity, this simple series RC circuit has many applications. Another commonly used capacitor circuit is the paralleled resistor-capacitor combination. While not as common as the series RC circuit, you can frequently find the parallel RC circuit in electronic equipment. In this section, you will investigate the operation and characteristics of both series and parallel RC circuits.

Series RC Circuits

The simplest form of RC circuit is a single capacitor connected in series with a resistor. Figure 3-17 shows such a circuit connected to an AC voltage source. The source voltage is a sine wave, designated E, which causes current to flow in the circuit. The capacitor charges and discharges as the input voltage varies. The charging and discharging action of the capacitor causes a movement of electrons in the circuit. The charge on the capacitor causes a voltage to be developed across it. This voltage is designated E_C as shown in Figure 3-17. The voltage across the capacitor is a sine wave that lags the current flowing in the circuit by 90°. As you learned earlier, the current in a capacitive circuit leads the voltage across the capacitor by 90°.

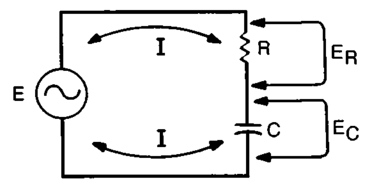


Figure 3-17
Series RC circuit.

The current in the circuit passes through resistor R and develops a voltage drop across it. The voltage across the resistor, designated E_R, is in phase with the current in the circuit. The voltage dropped across the resistor is a function of the resistor's value and the circuit's current ($E_R = I\,R$). The capacitor's voltage drop is a function of the current flowing in the circuit and the capacitive reactance ($E_C = I\,X_C$).

Figure 3-18 shows the phase relationships of the various voltages and currents in this series RC circuit. In this illustration, the current sine wave, I, is used as the reference. As you should recall, one of the fundamental characteristics of a series circuit is that the current is common to all components. Note the voltage drop across the resistor (E_R). This voltage drop is in phase with the current. To see this, note that the maximum, minimum, and zero crossing points for the voltage waveform coincide with those of the current waveform.

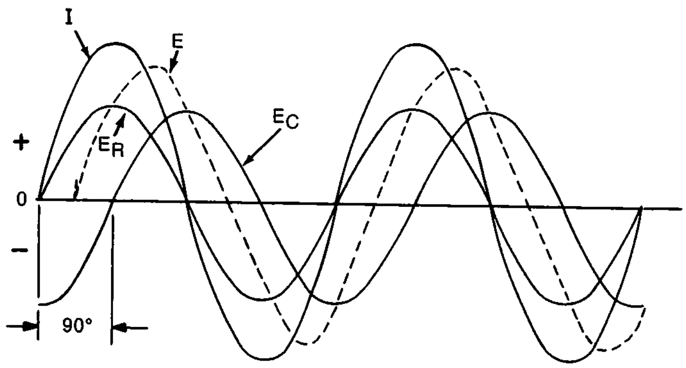


Figure 3-18
Phase relationships between the current and voltage in a series RC circuit.

Now refer to the capacitive voltage drop E_C. The current through a capacitor leads the voltage across it by 90°. Another way of saying this is that the voltage across the capacitor lags (occurs later in time) the current.

Another important characteristic of capacitive AC circuits is that Kirchhoff's Law also applies. Kirchhoff's Voltage Law states that the sum of the voltage drops across the components in a series circuit must equal the applied voltage. This law is valid for the circuit in Figure 3-17. Now refer to Figure 3-18. To add E_R and E_C, you sum the amplitudes of the two sine waves at multiple points and plot the resulting curve. When you do this, you will obtain the sine wave represented by the dashed line in Figure 3-18. This waveform represents the applied voltage (E). Note that its amplitude is higher than either the resistor voltage or the capacitor voltage as you would expect. Another important point is that the applied voltage is not in phase with the current or with either the capacitor or resistor voltages. The current in the circuit leads the applied voltage as it will in any capacitive circuit. But since the circuit is not purely capacitive, the current leads the applied voltage by some angle less than 90°.

In this example, the current leads the applied voltage by approximately 45°. This difference in phase is called the phase shift or, more commonly, the phase angle. Shortly, you will see how the word angle comes into play.

If a circuit has no resistance, it is purely capacitive and the current through the circuit leads the applied voltage by 90°. On the other hand, if the circuit is purely resistive, the current and voltage are in phase. When both resistors and capacitance are present in a circuit, the phase difference between the current and the applied voltage is some value between 0° and 90°.

The exact amount of the phase shift is determined by the amount of resistance and capacitive reactance in the circuit. Before you get into phase angle calculations, take a closer look at the voltage relationships in a series RC circuit.

When you use Kirchhoff's Law to analyze a series RC circuit, you must realize that it is not possible to directly add the numerical values of the voltage drops across the resistive and capacitive components of the circuit to obtain the applied voltage. The voltage drops across the resistance and the capacitive reactance are not in phase with one another. In order to obtain the correct applied voltage, you must correct for the phase difference between the two voltages. You can do this by vector addition.

Vector Diagrams

In the physical world, there are quantities that are expressed in specific units. Ohms, inches, and pounds are all examples of these quantities. These quantities are measured in scalar values and, in order to find the sum of a number of like quantities, you just add them together. For example:

$$5\ \Omega + 10\ \Omega = 15\ \Omega$$

Problem solving with scalar quantities is easy enough because it involves simple addition.

Other physical quantities have two properties; magnitude and direction. Any quantity that has both magnitude and direction is called a vector. Miles traveled in a northeast direction, altitude gained in feet while traveling west, and volts at 90° are all examples of vector quantities.

It is possible to add vectors but you must take into consideration both the magnitude and the direction of the vector. In order to make this easier, you should draw a vector diagram when you analyze AC circuits. The basic format for vector diagrams is shown in Figure 3-19.

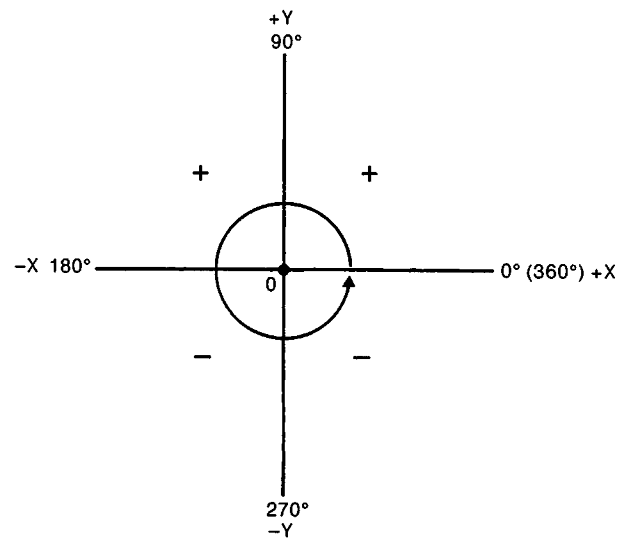


Figure 3-19
Vector diagram format.

This illustration consists of two lines, axis, which are perpendicular to each other. The horizontal line is the X axis and the vertical line is the Y axis. The point at which these two lines cross is the origin and it is labeled zero. You measure the magnitude, or value, of any vector outward from the origin. The direction of a vector corresponds to its phase differences in degrees. As you can see in Figure 3-19, the ends of the axis are labeled 0 (360), 90, 180, and 270. When you rotate the vector, it starts at 0 and travels in a counterclockwise direction until it reaches 360. This is one complete revolution and ends at the origin. Now that you are familiar with the basic groundwork of the vector diagram, look at an example.

Figure 3-20 shows the vector diagram of a series RC circuit. A current vector, I, is shown on the X axis pointing to the right. This vector represents the value of the current flow in the series RC circuit. It is a reference vector for the diagram because the current value is the same at all points in a series circuit. Coinciding with this vector is another vector labeled E_T. The length of this vector, from the origin to the point of the vector, represents the voltage dropped across the resistive portion of the circuit. This is the actual voltage as it would be measured with a voltmeter. It is an effective, or rms, voltage and is equal to .707 times the peak voltage across the resistor. The voltage vector overlaps the current vector because they are in phase.

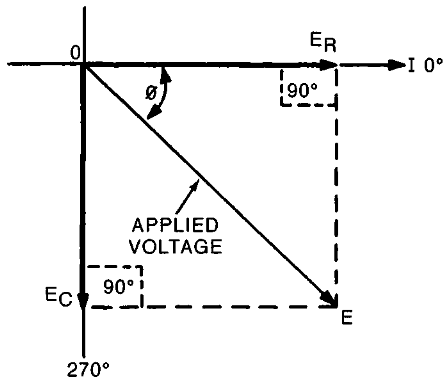


Figure 3-20
Vector diagram of a series RC circuit.

The voltage across the capacitor is labeled E_C. This is the actual voltage that is measurable across the capacitor and it is an effective value. Note that the direction of the capacitor voltage is shifted 90° from the direction of the resistor voltage. This is because there is a phase shift between the resistive and capacitive components in the circuit.

The applied voltage, the voltage supplied to the circuit, is the vector sum of the capacitor and resistor voltages. To graphically accomplish the vector addition, first use the resistor and capacitor voltages to form a rectangle. This is shown by the dashed lines in Figure 3-20.

The magnitude, or value, of the applied voltage is the distance from the origin to the far corner of the completed rectangle. Stated another way, the value of the applied voltage is represented by the diagonal line that is drawn from the origin across the rectangle.

The angle formed by the applied voltage vector and the resistive voltage vector represents the amount of phase shift that exists between circuit current and circuit voltage. This angle is always between 0 and 90 degrees. Later you will learn how to calculate this value but, for now, you need to know more about vector addition.

You can now use the illustration created by the graphic solution of vector addition to determine the actual applied voltage. The diagonal line that represents the applied voltage splits the rectangle into two triangles. These triangles are right triangles because they each have a 90° angle as shown in Figure 3-20. In addition, you also know the length of two sides of the triangles, represented by the capacitor and resistor voltages.

When you know the value, or length, of any two sides of a right triangle, you can use a mathematical formula called the Pythagorean Theorem to determine the value of the third side. Appendix A of this unit describes this theorem in detail. If you are not familiar with the Pythagorean Theorem, refer to Appendix A at this time. Once you understand this theorem, return to this point and continue your study.

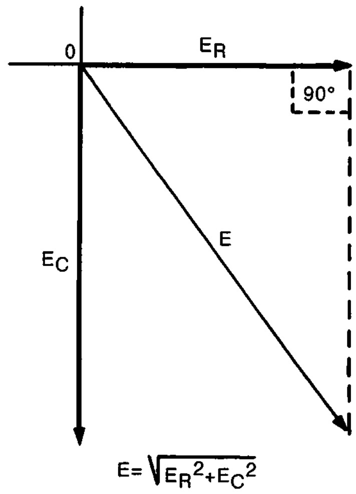


Figure 3-21
Voltage vector triangle of a series RC circuit.

In Figure 3-21, the side of the triangle that represents the applied voltage is the side directly opposite the 90° angle. This side is called the hypotenuse and you can use the Pythagorean Theorem to compute its length.

$$E = \sqrt{(E_R)^2 + (E_R)^2}$$

This expression indicates that if you square the resistor voltage and add it to the square of the capacitor voltage, and then take the square root of the sum, the result is the applied voltage.

You can rearrange the equation, to find the applied voltage, when you know the resistor and capacitor voltages. You can compute the resistor voltage if you know the applied voltage and capacitor voltage, or you can compute the capacitor voltage if you know the applied voltage and resistor voltage. These two formulas are:

$$E_R = \sqrt{(E)^2 - (E_C)^2}$$

$$E_C = \sqrt{(E)^2 - (E_R)^2}$$

The examples below show the use of the formulas.

1. What is the applied voltage in a series RC circuit where the resistor voltage is 12 volts and the capacitor voltage is 18 volts?

$$E = \sqrt{(E_R)^2 + (E_C)^2}$$

$$E = \sqrt{12^2 + 18^2}$$

$$E = \sqrt{144 + 324}$$

$$E = \sqrt{468}$$

$$E = 21.63 \text{ volts}$$

2. The voltage applied to a series RC circuit is 115 volts. The current in the circuit is .0075 amperes. The resistor value is 5 kilohms. What is the capacitor voltage?

$$5k = 5000$$

First, calculate the resistor voltage:

$$E_R = IR$$

$$E_R = .0075\ (5000)$$

$$E_R = 37.5 \text{ volts}$$

Next, calculate the capacitor voltage:

$$E_C = \sqrt{(E)^2 - (E_R)^{?}}$$

$$E_C = \sqrt{115^2 - 37.5^{?}}$$

$$E_C = \sqrt{13225 - 1406.25}$$

$$E_C = \sqrt{11818.75}$$

$$E_C = 108.7 \text{ volts}$$

Note that anytime you know any 2 sides of a right triangle, you can use Pythagorean Theorem to calculate the third side.

Impedance

Impedance is the total opposition to current flow in an AC circuit. In a circuit that consists of a resistor and a capacitor, the total opposition is the sum of the capacitive reactance and the resistance. Both the reactance and the resistance impede current flow. Due to the phase shift created by the capacitor, you cannot directly sum the capacitive reactance and resistance, just as you cannot directly sum the voltage drops across the capacitor and resistor in a series RC circuit. The impedance is the vector sum of the capacitive reactance and resistance.

The impedance of an AC circuit is expressed in ohms and is designated by the letter Z. You can define the impedance in terms of Ohm's Law just as you defined the total resistance of a DC circuit. The impedance of an AC circuit equals the applied voltage divided by total circuit current:

$$Z = \frac{E}{I}$$

You can use basic algebra to rearrange this expression to obtain the expressions for voltage and current in terms of the circuit impedance:

$$E = IZ$$

$$I = \frac{E}{Z}$$

In the previous section, you saw that due to the phase shift caused by the capacitor in a series RC circuit, you cannot directly add the voltage drops across the capacitor and resistor to obtain the applied voltage. Instead, you had to calculate a vector sum to obtain the correct value. The voltage drops across the resistor and capacitor in a series RC circuit are directly proportional to the current. Since the current through a series circuit is the same in all components, you can say that the voltage drops across the circuit components are directly proportional to their resistance or reactance. For that reason, you can draw a diagram exactly like the voltage vector diagram that you learned about earlier to obtain the total impedance of the circuit. This vector diagram is shown in Figure 3-22. Here, the current vector is again used as the reference. The resistance vector coincides with the current vector because the resistive voltage drop is in phase with current. In this case, the length of the vector is proportional to the resistance.

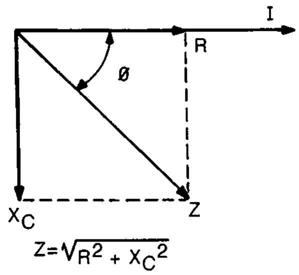


Figure 3-22
Impedance vector diagram
of a series RC circuit.

Another vector that represents the magnitude of the capacitive reactance, X_C, is drawn 90° out of phase with the resistance vector to take into account the 90° phase shift produced by the capacitor. Complete the rectangle that is formed by the resistance and reactance vectors and draw the diagonal line as indicated to obtain the magnitude of the impedance. The length of the diagonal line represents the total opposition to current flow. With Pythagorean's theorem, you can write an expression for the impedance of the circuit in terms of the resistance and reactance:

$$Z = \sqrt{R^2 + X_C^2}$$

This expression shows that the impedance is equal to the square root of the sum of the resistance squared and the capacitive reactance squared. You can use basic algebra to rearrange this formula to compute the circuit resistance in terms of the impedance and reactance, or the capacitive reactance in terms of the impedance and resistance:

$$R = \sqrt{Z^2 - X_C^2}$$

$$X_C = \sqrt{Z^? - R^2}$$

The following examples show you how to use these formulas.

1. What is the impedance of a series RC circuit with a resistance of 50 ohms and a reactance of 75 ohms?

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{50^2 + 75^2}$$

$$Z = \sqrt{2500 + 5625}$$

$$Z = \sqrt{8125}$$

$$Z = 90.14 \text{ ohms}$$

2. A series RC circuit has an applied voltage of 120 volts. The current is .02 amperes. The circuit resistance is 4000 ohms. What is the capacitive reactance?

$$Z = \frac{E}{I}$$

$$Z = \frac{120}{.02} = 6000 \text{ ohms}$$

$$X_C = \sqrt{Z^2 - R^2}$$

$$X_C = \sqrt{6000^2 - 4000^2}$$

$$X_C = \sqrt{36000000 - 16000000}$$

$$X_C = \sqrt{20000000}$$

$$X_C = 4472 \text{ ohms}$$

Power in AC Circuits

Whenever an AC voltage is applied to a resistance, current flows and electrical energy is converted into heat energy. The heat energy, or power, is dissipated in the resistance. All of the basic formulas for computing power dissipation in resistive DC circuits are applicable to power computation in a resistive AC circuit:

$$P = EI$$

$$P = I^2R$$

$$P = \frac{E^2}{R}$$

When you use these formulas to compute AC power dissipation, make sure the voltage and current are the effective, or rms, values.

Figure 3-23 is a diagram of the voltage, current, and power in an AC resistive circuit. Note that the applied voltage and the current are in phase. To obtain power, multiply the instantaneous values of current and voltage, and plot the resulting products as a power curve. The instantaneous values are the values of current and voltage at any given instant in time during each current and voltage cycle.

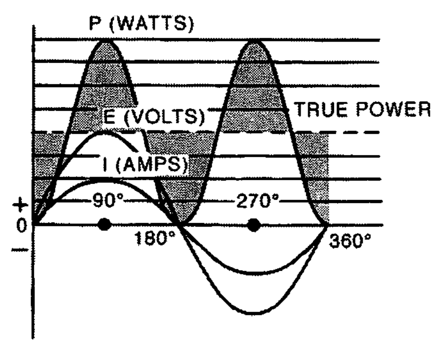


Figure 3-23
Power in a resistive AC circuit.

The product of a positive voltage and a positive current is shown as the first positive power peak. When you multiply the negative current and voltage, you get another positive peak. The power curve is positive and sinusoidal in shape.

Since the entire power curve is positive, it is possible to determine the actual power dissipated if you draw a line halfway between the maximum and zero points on the power curve. The value that is represented by this line is the product of the rms values of current and resistance in the circuit. For this reason, it is called true power. Since power is dissipated only in resistance, the true power is the only power dissipated in an AC circuit.

When you analyze an AC circuit, power appears to be dissipated by both inductive and capacitive components. However, due to the phase shift between the current and voltage through reactive components, they do not actually dissipate power. Figure 3-24 shows why.

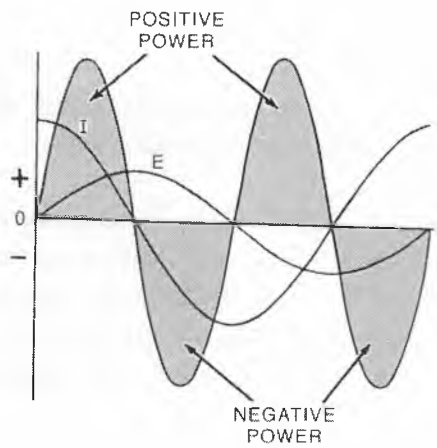


Figure 3-24
Power in a purely capacitive circuit.

In a purely capacitive circuit, current leads the applied voltage by 90°. To compute the power in this circuit, multiply the instantaneous values of current and voltage and plot the resulting power curve. Unlike the resistive power curve in Figure 3-23, the power curve in a purely capacitive circuit is both positive and negative. What this power curve tells you is that during one half cycle of the applied voltage, the capacitor appears to consume power. This is indicated by the positive part of the power curve. During the other half cycle, the power is negative. It is during this time that the capacitor actually acts as the supply and furnishes power to the source. When the capacitor charges, it consumes power. When it discharges, it gives power back to the circuit. Since the positive and negative power curves are equal and opposite, the total average effect is zero. This means that no power is dissipated in a purely capacitive circuit.

Figure 3-25A illustrates the power in an AC circuit that contains both capacitance and resistance. Note that the current leads the voltage by some angle less than 90°. With this condition, the positive power is greater than the negative power. The negative power is still the result of the ability of a capacitor to store a charge

and then return it to the circuit. The curve indicates that the resistor is dissipating power in the form of heat. Since a purely capacitive circuit dissipates no power, a purely resistive circuit dissipates all of the power in the form of heat. But in a circuit that contains both resistance and reactance, power is dissipated only in the resistance.

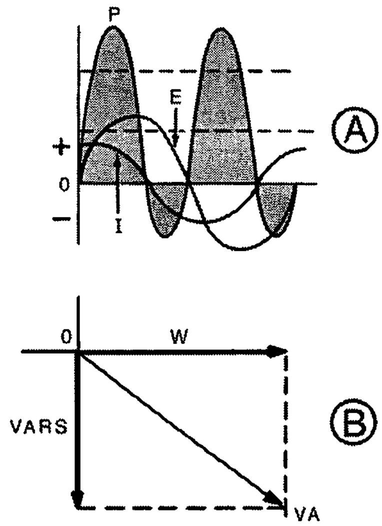


Figure 3-25
Power dissipation in a series RC circuit.

It is possible to construct a vector diagram for the power that is used, or appears to be used in an RC circuit. Such a diagram is shown in Figure 3-25B. In this diagram, the true power measured in watts (W), is shown on the X axis. The power that appears to be dissipated by the capacitive portion of the circuit measured in volt/amps reactive (VARS), is shown on the Y axis. The vector sum of the watts and volt/amps reactive is called apparent power. The unit of measure for apparent power is the volt/amp (VA).

You can use the appropriate Ohm's Law power formula to calculate all of the values that are used in the power triangle. For example, the power that is dissipated by the resistive portion of the circuit is the product of the voltage drop across the resistor and the current through the resistor. The apparent power is the product of the applied voltage and circuit, or total, current. The volt/amps reactive is the product of the voltage drop across the capacitive component and the circuit current.

POWER FACTOR

When you use the formula P = EI to compute the power in a circuit that contains both resistance and capacitance, you obtain a value called apparent power. It is called apparent power because power *appears* to be dissipated because an applied voltage causes current to flow. In a purely capacitive circuit, current does flow when an AC voltage is applied. However no real power is dissipated. In a purely reactive circuit, one that contains only a capacitor, this apparent power is sometimes referred to as reactive power. In a circuit that contains both resistance and capacitance, the apparent power includes both the true power dissipated in the circuit resistance, and the power that appears to be dissipated in the capacitor.

The ratio of the true power to the apparent power in an AC circuit is referred to as power factor, PF. This is expressed in the formula:

$$PF = \frac{\text{true power}}{\text{apparent power}} = \frac{\text{watts}}{\text{volts / amps}}$$

The power factor is an excellent indication of the relative amounts of resistance and reactance in a given circuit. In a purely resistive circuit, the true power and the apparent power are equal. Therefore, the power factor is one. In a purely reactive circuit, such as one that contains only a capacitor, the true power is zero. For circuits that contain both resistance and reactance, the power factor is always some value between zero and one. The greater the power factor, the more resistive the circuit. The lower the power factor, the greater the circuit reactance.

More importantly, however, the power factor is an indication of the efficiency of a circuit. In any circuit, work is performed only by the current that flows through the resistive portion of the circuit. The reactive current performs no work.

Later in the course, during the discussion of tuned circuits, you will learn how you can change the power factor of a circuit and make the circuit operate more efficiently.

In a series RC circuit, you can also use the values of the resistance and the reactance in the circuit to determine the power factor. In fact, the power factor is equal to the ratio of the resistance to the total impedance of the series RC circuit:

$$PF = \frac{R}{Z}$$

You can also determine power factor when you know the applied voltage and the voltage drop across the resistance in the circuit. In this case:

$$PF = \frac{E_R}{E_{APPLIED}}$$

Phase Shift

To compute the phase shift for an RC circuit, you have to use trigonometry. If you do not understand the fundamentals of trigonometry, refer to Appendix B at the end of this unit. After you review this appendix, return to this point and continue your study.

In a capacitive AC circuit, the current leads the applied voltage. In a purely capacitive circuit, the current leads the voltage by 90°. When a resistance is introduced into the circuit, the phase shift is something less than 90°. You can determine the exact amount of the phase shift in a circuit with basic trigonometry. Here's how.

As you know, for any AC circuit, it is possible to construct a voltage, impedance, and power vector diagram. Figure 3-26A is a series RC circuit. The impedance vector diagram is shown in Figure 3-26B, the voltage diagram in 3-26C, and the power diagram in 3-26D. As you can see, in each instance, vectors are used to construct a triangle. You can use the sine and cosine functions to determine the phase shift in this circuit.

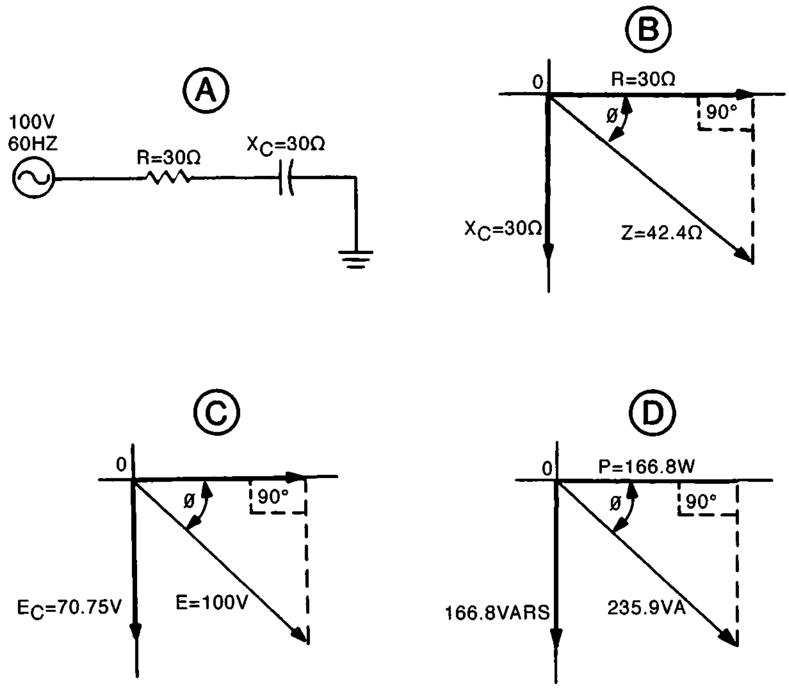


Figure 3-26
A typical series RC circuit.

The sine of an angle is equal to the value of the opposite side divided by the hypotenuse. The sine of the impedance triangle equals:

$$\frac{30\ \Omega}{42.4\ \Omega} = .707$$

Once you know the sine of the angle, just use the table located in Appendix C of this unit to find that the phase shift for the circuit is 45°.

You can also use the cosine of the angle to determine the phase shift. This time, however, use the values from the power triangle. The cosine of the angle equals:

$$\frac{A}{H} = \frac{166.8\ W}{235.9\ VA} = .707$$

Again, if you refer to the table in Appendix C, you find that the phase shift is 45°.

Remember that .707 is the rms or effective value of a sine wave. It is also the point where the voltage and current waveforms intersect when the resistance and capacitive reactances are equal. The angle of 45° and the numerical value of .707 are extremely important in electronics.

You may have noticed that when you calculated the cosine of the angle, you divided the true power by the apparent power. Recall that true power divided by the apparent power equals the power factor of the circuit. Therefore:

$$PF = \frac{\text{True Power}}{\text{Apparent Power}} = \cos \theta$$

Another relationship that you should be aware of is that the sine starts at 0° and increases to maximum at 90°. The cosine function is maximum at 0° and decreases to minimum at 90°. The sine and cosine waves intersect once each 90° at an angle of 45° (a numerical value of .707).

Trigonometry, Triangles, and Vector Diagrams

You can use the various trigonometric relationships to determine not only the phase shift of a circuit but also the length of any vector in a vector diagram when you know the lengths of the other two vectors.

Look again at Figure 3-26C. Assume that you know the applied voltage, 100 volts, and the voltage drop across the resistance in the circuit, 70.75 volts. In order to determine the voltage drop across the circuit capacitor, you must first

determine the phase shift. Since you know the resistive voltage and the applied voltage, use the cosine:

$$\cos = \frac{A}{H} = \frac{70.75\text{ V}}{100\text{ V}} = .707$$

Now refer to Appendix C and find that the angle that has a cosine of .707 is approximately 45°. Once you know the angle, look up the sine of the angle. This, again, is .707. Now use the formula:

$$\sin = \frac{O}{H}$$

or

$$.707 = \frac{E_C}{100\text{ V}}$$

now transpose:

$$.707 \times 100\text{ volts} = 70.7\text{ volts.}$$

At an angle of 45°, the voltage drop across the capacitive portion of the circuit is 70.7 volts.

Parallel RC Circuits

Thus far, your study of RC circuits has been limited to series RC circuits. It is also possible to connect RC circuits in parallel configurations. An elementary parallel RC circuit is shown in Figure 3-27.

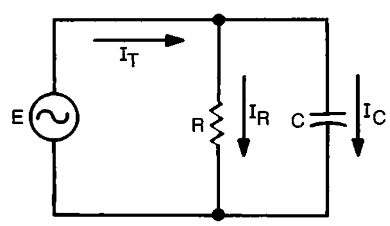


Figure 3-27
Current vector diagram of a parallel RC circuit.

As with the series RC circuit, Ohm's Law applies to all of the components within the circuit. Also, as with the series RC circuit, when you determine circuit unknowns, it is necessary to use vector addition. However, when you draw vector diagrams for parallel circuits, there is one major difference.

As you know, in a series circuit, current is used as a reference because it is the same at all points in the circuit. In a parallel RC circuit vector diagram you must use voltage as a reference. Remember, the voltage across all branches of a parallel circuit are equal. You will now look at a basic circuit and some vector diagrams to see exactly what differences there are.

Figure 3-28A shows an elementary RC parallel circuit. In this circuit, the voltage drop across both the resistor and the capacitor is 100 volts. Since you know the voltage drop as well as the capacitive reactance and resistance, it is possible to use Ohm's Law to determine the current through the components.

$$I = \frac{100\ V}{100\ \Omega} = 1\ A$$

and:

$$I = \frac{100\ V}{50\ \Omega} = 2\ A$$

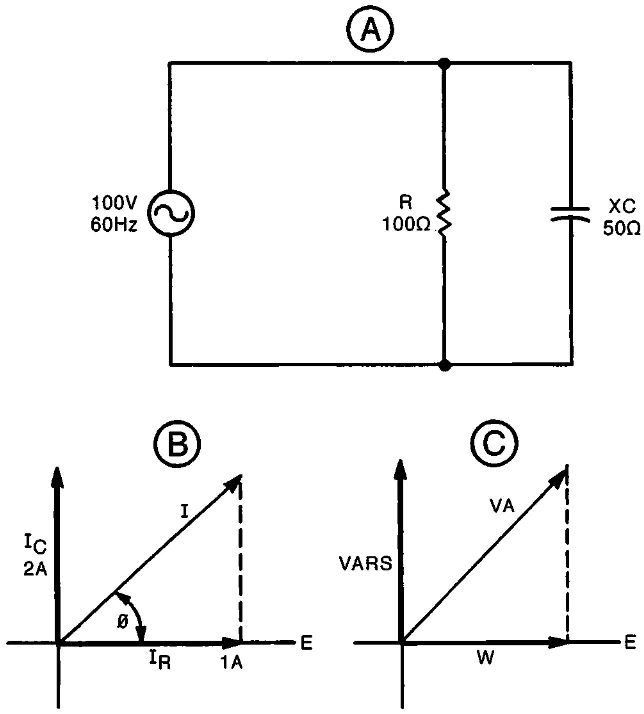


Figure 3-28

The vector diagram that uses these two values is shown in Figure 3-28B. You can now find the circuit current with either the Pythagorean Theorem or trigonometric functions. The Pythagorean Theorem method is shown here:

$$I = \sqrt{I_R^2 + I_C^2}$$

$$I = \sqrt{1^2 + 2^2}$$

$$I = 2.23 \text{ A}$$

The trigonometric method is somewhat more roundabout, but you can also use it.

First, use the available information to form one of the basic trigonometric functions. For the current triangle, you know both the opposite and adjacent sides. This is the tangent function. Therefore:

$$\tan\theta = \frac{O}{A} = \frac{2\text{ A}}{1\text{ A}} = 2$$

Refer now to the table in Appendix C and you find that a 64° angle has a tangent of 2.

The next step is to find either the sine or the cosine of the 64° angle. For this example, use the sine value, .899. Now put the known values into the proper trigonometric equation:

$$\sin\theta = .899 = \frac{O}{A} = \frac{2\text{ A}}{I}$$

now transpose:

$$I = \frac{2}{.899} = 2.23 \text{ A}$$

You can also solve the triangle for the power vector diagram (Figure 3-28C) with Ohm's Law, the Pythagorean Theorem, and the various trigonometric functions.

One more thing about parallel RC circuits. You may have noticed that an impedance vector diagram is not shown in Figure 3-28. This is because the impedance triangle for a parallel circuit is somewhat unique. You may recall from your study of DC electronics that the resistance of a parallel circuit is always less than the smallest resistive branch in the circuit. The same general principle holds true for impedance in a parallel RC circuit. The impedance is always less than the smaller of the two current-opposing components.

For this reason, when you construct the impedance vector diagram, you must use the reciprocal of the resistance and capacitive reactance, and the resulting vector will be the reciprocal of the actual impedance.

Figure 3-29 illustrates this point. Note that the total impedance is less than either the capacitive reactance or the resistance. If you wish to use either the Pythagorean Theorem or any of the trigonometric functions to solve for impedance, you must always use reciprocal values. Since reciprocal values are harder to work with than standard numerical values, it is best, when possible, to use Ohm's Law to obtain impedance, resistance, or capacitive reactance.

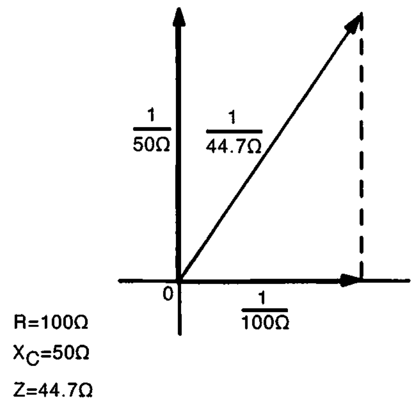


Figure 3-29

However, if only the capacitive reactance and resistance are available, you can use this derivation of the parallel resistance formula to calculate impedance:

$$Z = \frac{RX_C}{\sqrt{R^2 + X_C^2}}$$

As you have probably noticed, there are any number of ways to obtain the correct results when you analyze AC circuits. The key is to be extremely familiar with the trigonometric relationships as well as Pythagorean's Theorem. Be sure that you have mastered these formulas before you proceed with the remainder of this text.

Programmed Review

73. In an AC circuit that contains only capacitance, the current and applied voltage are out of ___________.

74. (phase) The characteristics of a capacitor cause the current to ___________ the voltage.

75. (lead) The phase angle in a purely capacitive circuit is __________ degrees.

76. (90) In a purely resistive AC circuit, the current and voltage are in step with one another. In other words there is no __________ __________.

77. (phase shift) The current and voltage are in phase in a resistive AC circuit. The phase angle is 0°. When capacitance and resistance are combined in an AC circuit, the current still ___________ the applied voltage.

78. (leads) The phase angle is between __________ and __________ degrees.

79. (0, 90) The phase shift is more than 0° but less than 90°. The actual value of phase shift in a series RC circuit is a function of the _____________ and _____________ _____________.

80. (resistance, capacitive reactance) The R and C values determine the phase angle. More specifically, the phase shift depends upon the resistance and capacitive reactance. Capacitive reactance is a function of the capacitance and ______________.

81. (frequency) The phase shift is frequency sensitive. You can use a number of expressions to determine the actual phase shift. One of them is:

$$\tan = \frac{O}{A} = \frac{X}{R}$$

With this expression, you can determine the tangent of the angle theta, Now, use the tangent ratio and the tables in Appendix C to calculate the phase shift in a circuit where R = 1280 ohms and X = 1000 ohms. degrees.

Phase shift = __________ degrees.

82. (38) $\tan \theta = \frac{1000}{1280} = .781$

Look up .781 in the tangent column and you can see that it corresponds to 38°. In a series RC circuit, the applied voltage divides between the components according to their resistance and reactance. The current is the same in all components. Therefore, you can use Ohm's Law to compute the voltage drops. The resistive voltage drop E_R = __________.

83. (IR) The capacitor voltage drop is E_C = __________.

84. (IX_C) The sum of the voltage drops is equal to the source voltage. True or false? __________.

85. (false) You cannot directly add the voltage drops to obtain the applied voltage due to the phase difference between the resistive and reactive drops. To obtain the applied voltage, you must add the voltage drops with __________.

86. (vectors) A voltage vector is a line whose length represents the __________ of the voltage and its direction represents its __________.

87. (amplitude, phase) You can carry out vector addition of voltages graphically on a vector diagram, but can also accomplish the addition with the formula ____________.

88. $Z = \sqrt{(E_R)^2 + (E_C)^2}$ This formula is Pythagorean's theorem for voltages. If the resistor voltage is 9 volts and the capacitor voltage is 11 volts, the applied voltage E is __________ volts.

89. (14.2) $E = \sqrt{9^2 + 11^2} = \sqrt{81 + 121} = \sqrt{202} = 14.2$ The total opposition to current flow in an AC circuit is called ____________.

90. (impedance) You determine the impedance with the values of __________ and __________ __________ in a circuit.

91. (resistance, capacitive reactance) You compute the impedance with the formula ____________.

92. $(Z = \sqrt{R^2 + X_C^2}\,)$ The impedance of a circuit where R = 47 ohms and X_c = 80 ohms is __________ ohms.

93. (92.8) $Z = \sqrt{47^2 + 80^2} = \sqrt{2209 + 6400} = \sqrt{8609} = 92.8$ ohms. The phase angle of this circuit is ________ degrees.

94. (59.6) $\tan\theta = \frac{X_C}{R} = \frac{80}{47} = 1.7$

When you use the correct table, you find H = 59.6°. If you know the applied voltage and the total current, you can determine the impedance of the circuit with the formula __________.

95. $(Z = \frac{E}{I})$ In an AC circuit, power is dissipated only in the ____________.

96. (resistance) This power is called __________ power.
97. (true) An AC circuit that contains both resistance and reactance appears dissipate more power than it actually is. To determine this power, you multiply the applied voltage and the total circuit current (P = EI). This is called __________ power.
98. (apparent) The apparent power is always __________ than the true power.
99. (greater) In a parallel RC circuit, the phase shift is such that the total circuit current __________ the applied voltage.
100. (leads) You can compute the impedance of a parallel RC circuit with the formula __________ when you know the resistance and reactance.
101. ($Z = \frac{RX_C}{\sqrt{R^2 + X_C^2}}$)

EXPERIMENT 3

RC Circuits

OBJECTIVES:

To demonstrate the characteristics of an (RC) resistor-capacitor AC circuit.

To compare calculated AC circuit values with the corresponding measured values.

To examine the effects on total capacitance when you connect capacitors in series or parallel.

To observe accurate measurements by rotating components towards the ground before you make new measurements.

To calculate total capacitance in both series and parallel circuits.

Material Required

Heathkit Analog Trainer
AC Voltmeter
1 — 0.039 μF capacitor
1 — 0.1 μF capacitor
1 — 0.47 μF capacitor
1 — 4.7 kΩ, 1/2-watt resistor (yellow-violet-red)

Procedure

1. Construct the circuit shown in Figure 3-30A. Be sure to observe polarity when you construct this circuit. As with the last experiment, you must observe proper grounding because both the trainer and your test instrument may share a common ground. You will use the 15-volt, 60 Hz line source as the applied voltage.

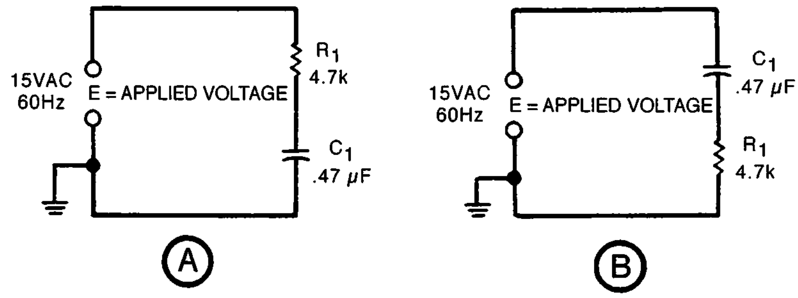


Figure 3-30
Experimental circuit for Experiment 3.

2. Use your AC voltmeter to measure the voltage source that is connected to the circuit. To do this, connect the negative voltmeter probe to ground and the positive probe to one of the 15 VAC terminals of the power supply. The voltage that you measure may be slightly above or below 15 VAC. Record your voltage in the space provided below:

E_A = __________ volts

The voltage you measured here is expressed in terms of which value? Check the correct answer.

A. average
B. rms
C. peak
D. peak-to-peak

3. With the resistor and capacitor values given in Figure 3-30, and the voltage you measured in step 2, compute the following:

Capacitive reactance	X_C =	__________	ohms
Impedance	Z =	__________	ohms
Current	I =	__________	amperes
Resistor voltage	E_R =	__________	volts
Capacitor voltage	E_C =	__________	volts
Phase angle	θ =	__________	degrees
Power	P =	__________	watts

4. Be sure your meter is properly grounded; then measure the voltage across capacitor C_1 in the circuit shown in Figure 3-30A. Record this voltage in the space provided below:

E_C = __________ volts

Now, turn off the trainer and construct the circuit shown in figure 3-30B. Note that you can either swap the components, or switch the power supply leads.

When you rotate the components to your ground reference point, this helps you avoid the problem of ground loops. These ground loops cause inaccurate readings which can lead to large discrepancies between your calculated and measured values.

Turn on your trainer and measure the voltage drop across R_1. Record the value in the space provided below:

E_R = __________ volts

5. Add the resistor and capacitor voltages that you measured above and record the sum in the space provided below:

$E_R + E_C$ = __________ volts

Does the sum of the resistor and capacitor voltage equal the applied voltage that you measured in step 1? __________ If not, why? __________

____

6. Use your measured resistor voltage and the resistance to compute the circuit current. Record your value in the space provided below:

I = __________ amperes

Does the circuit current you computed agree with the current value you calculated in step 3? __________ If not, why? __________

____

7. Use the values of resistance, reactance, and impedance for this circuit to construct a vector diagram. Indicate the value of the phase angle.

Discussion

In the first step of this experiment, you constructed a simple RC series circuit. The power for the circuit is supplied by the 60 Hz line source on your Trainer.

Next, you measured the line voltage with your AC voltmeter. This value may vary from the nominal 15 VAC value. It is not critical that you have exactly 15 volts. But, it is extremely important that you know the true voltage output from the power supply so that you can make accurate computations of other circuit values.

The line voltage is measured in rms, or effective, value.

The next step of this experiment required you to use certain known values, such as resistance, capacitance, and applied voltage to calculate various circuit characteristics. An example of appropriate calculations follows. Be aware that there are many ways to compute unknown quantities for an AC circuit. It is not necessary that you use the exact format that follows. Arriving at the correct answer by the correct application of theory is the important point. At any rate, here are the answers.

$$X_C = \frac{1}{2\pi fC} = \frac{1}{(6.28) \times (60) \times (.00000047)} = 5645.4 \text{ ohms}$$

It is now possible to perform a vector addition of the resistance and capacitive reactance in the circuit to determine the circuit impedance. To do this you can use the Pythagorean Theorem.

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{4700^2 + 5645.4^2}$$

$$Z = \sqrt{22{,}090{,}000 + 31{,}870{,}541}$$

$$Z = \sqrt{53{,}960{,}541} = 7345.8 \text{ ohms}$$

After you calculate the impedance, use Ohm's Law to compute the circuit current:

$$I = \frac{E}{Z} = \frac{15}{7345.8} = .00204 \text{ amperes}$$

Since you know that current is the same along all points in a series circuit, you can use the circuit current you calculated in the previous step along with the values of capacitive reactance and resistance to determine E_C and E_R:

$$E_R = I_R R = .00204\ (4700) = 9.59 \text{ volts}$$

$$E_C = IX_C = .00204\ (5645.4) = 11.52 \text{ volts}$$

You can now determine the phase angle, or shift, for the circuit. First, find the tangent of the angle theta. To do this, find the ratio of the capacitive reactance to the resistance.

$$\tan\theta = \frac{X_C}{R} = \frac{5645.4}{4700} = 1.2$$

Then check the table in Appendix C to determine the phase angle.

$$\theta = 50°$$

You can use the following formula to determine the true power in watts:

$$P = I^2R = (.00204)^2\ 4700 = .0195 \text{ watts or } 19.5 \text{ milliwatts}$$

The voltages you measured in step 4 should compare favorably with your calculated values in step 3. By rotating the components to reposition ground helped you insure a greater degree of accuracy. Your results should have been fairly close, although there still may be differences caused by component tolerances, as well as poor AC meter sensitivity and frequency response.

The sum of the resistor and capacitor voltages you calculated in step 5 exceeds the applied voltage measured in step 2. This is because the applied voltage you measured in step 2 is actually the vector sum of the resistor and capacitor voltages. If you use the resistor and capacitor voltages to construct a voltage vector diagram, you will find that the vector sum of these two voltages does equal the applied voltage.

In step 6, you used the resistor voltage and resistance in an Ohm's Law calculation to determine the circuit current. This current agrees with the calculation from step 3. This is because current is the same at all points in a series AC circuit.

Finally, a vector diagram which shows resistance, reactance, impedance, and phase angle is shown in Figure 3-31.

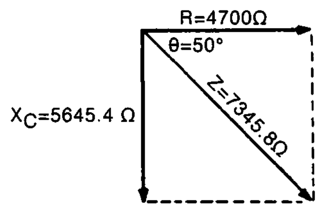


Figure 3-31
Impedance vector diagram for experiment circuit.

Procedure (continued)

In the following steps you will show the effect of connecting capacitors in parallel and in series.

8. Construct the circuit shown in Figure 3-32A. Note that this circuit is similar to the experimental circuit you constructed from Figure 3-30A. The only difference is that two additional capacitors have been added. These two capacitors are connected in parallel with the 0.47 µF capacitor in the original circuit.

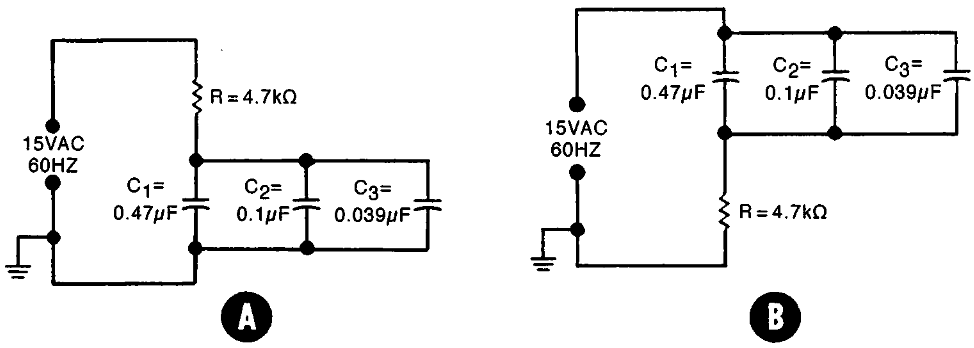


Figure 3-32
Experimental circuits for steps 8 through 13.

9. Use the rules for parallel capacitance and the capacitive values given in Figure 3-32A to compute the total circuit capacitance. Record your total circuit capacitance below:

C_T = ____________ μF

10. Apply power to the experimental circuit. Use your AC voltmeter to measure the voltage across the parallel capacitor combination. Record this voltage below:

E_C = ____________ volts

Now, turn off the trainer and interchange the leads from the 15 VAC source. This, in effect, changes the circuit to the one shown in Figure 3-32B. Measure the voltage across the resistor and record this voltage below:

E_R = ____________ volts

11. Use the resistor voltage you measured in step 10 and the resistance of R to compute the current that flows in the circuit. Record this value of current in the space provided:

I = ____________ amperes

12. Use the capacitor voltage you measured in step 10 and the current you computed in step 11 to compute the capacitive reactance in the circuit. Record this value of capacitance reactance below:

X_C = ____________ ohms

13. Since you know the capacitive reactance and the frequency of the applied voltage, you can now calculate the total circuit capacitance. Record this value of capacitance in the space provided:

C_T = ____________ μF

How does your computed value of capacitance obtained in step 9 compare with the value obtained from measurements in step 13? Explain any discrepancies. ____________________________________

____

How does the total capacitance compare to the original circuit capacitance in Figure 3-30? ____________________________________

____

____

14. Modify the wiring in your experimental circuit so that it appears as shown in Figure 3-33A. Here, you connect the 0.47 μF and 0.1 μF capacitors in series. The capacitor voltage in this circuit is the voltage across both capacitors. Double check you wiring of the circuit to be sure that it is exactly as shown.

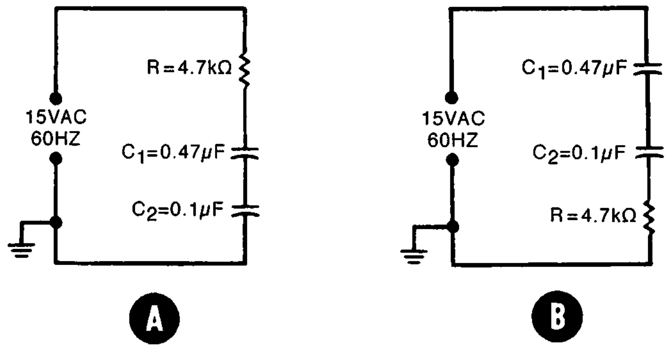


Figure 3-33
Experimental circuits for steps 14 through 19.

15. Use the rules for computing the total capacitance of two capacitors connected in series to find the total capacitance of the circuit in Figure 3-33A. Record your value below:

C_T = __________ μF

16. Apply power to your experimental circuit. Measure the voltage across the two capacitors that are connected in series. Record this voltage in the space provided below:

E_C = __________ volts

Turn off the Trainer and interchange the leads connected to the circuit. This results in the circuit shown in Figure 3-33B. Now, turn on the power and measure the voltage drop across the resistor in the circuit. Enter the voltage in the space below:

E_R = __________ volts

17. Use your measured resistor voltage and the resistance value to compute the circuit current:

I = __________ amperes

18. Use your measured capacitor voltage and the current you computed in step 17 to find the total capacitive reactance in the circuit:

X_C = ___________ ohms

19. Use your computed value of capacitive reactance and the frequency of the applied AC voltage to compute the total circuit capacitance. Record you value below:

C_T = ___________ µF

Discussion

In this part of the experiment you connected capacitors in parallel and in series and noted the effect this had on the total circuit capacitance. The purpose of this experiment is to verify the rules you learned earlier for computing the total value of capacitors connected in parallel and in series.

In steps 8 through 13, you demonstrated that the total capacitance of capacitors connected in parallel is simply the sum of the individual capacitors. In the circuit of Figure 3-30, the total circuit capacitance is:

$$C_T = C_1 + C_2 + C_3$$

$$C_T = .47\ \mu F + .1\ \mu F + .039\ \mu F = .609\ \mu F$$

To verify this total capacitance, you made measurements on the circuit. You measured the resistor voltage and then computed the circuit current. This same value of current flows through the capacitive portion of the circuit. Next, you measured the capacitor voltage. Since you now knew the voltage across the parallel capacitor combination and the circuit current, you were able to compute the capacitive reactance. Then with the capacitive reactance and the 60 Hz input frequency, you computed the total circuit capacitance. Your computed value should correspond very closely to the parallel sum indicated above. The total capacitance is greater than that of the original circuit. Due to capacitor tolerances and errors in measuring the AC voltage, your values could be as much as 20% off. However, the values should be close.

In step 14, you connected two capacitors in series. You computed the total equivalent capacitance and then made circuit measurements to verify this value.

The total capacitance of the 0.47 μF and 0.1 μF capacitors connected in series is indicated below:

$$C_T = \frac{C_1 C_2}{C_1 + C_2} = \frac{.47(.1)}{.47 + .1} = \frac{.047}{.57} = .0825\ \mu F$$

Note that this total value of capacitance is less than the smaller capacitor in the circuit.

To verify that the total circuit capacitance is your calculated value, you measured the resistor and capacitor voltages. With the resistor voltage and the circuit resistance you computed the circuit current. This circuit current is common to the capacitors in the circuit. You then used the voltage across both capacitors and the circuit current to compute the total reactance in the circuit. Since you now knew the reactance and the 60 Hz frequency, you computed the circuit capacitance. Again, your computed value should correspond to the value you computed earlier with the given capacitor values. The two values should agree, but allow for component tolerances and measurement errors.

Procedure (continued)

In the following steps you will demonstrate how changes in capacitance and frequency affect the capacitive reactance in the circuit.

20. In the previous steps, you already demonstrated the effect of changing the capacitance in a circuit. By assembling the data you accumulated earlier, you will see how changing the capacitance affects the reactance. In Figure 3-30 the total circuit capacitance is .47 μF. In Figure 3-32 the total circuit capacitance is .609 μF. In Figure 3-33 the total capacitance is .0825 μF. In each of these circuits, you computed the total capacitive reactance. Record the corresponding values of reactance for each capacitor in the spaces provided below:

    $C_T = .609\ \mu F$ $X_C =$ ___________ ohms
    $C_T = .47\ \mu F$ $X_C =$ ___________ ohms
    $C_T = .0825\ \mu F$ $X_C =$ ___________ ohms

21. When you study the data given in the step above, you should be able to draw some conclusions about how the reactance changes with a change in capacitance for a fixed frequency. Complete the following statements:

    When you increase the value of capacitance in a series RC circuit, the capacitive reactance ___________. When the value of capacitance decreases, the capacitive reactance ___________.

22. In this step you will show how capacitive reactance varies with frequency. Construct the circuit shown in Figure 3-34. You will use the sine-wave signal generated by the internal signal generator circuit on your trainer. Connect the SINE and GND outputs of the generator to the RC circuit you wired on the breadboarding socket. Set the range switch on the generator to the LOW position. Turn the frequency dial to the 200 Hz position.

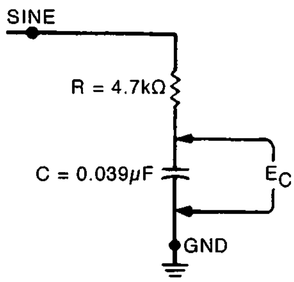


Figure 3-34
Experimental circuit for step 22.

23. Connect your AC voltmeter across the capacitor. Be sure you connect the ground lead of your meter to the GND side of the generator output. Apply power to the Experimenter and measure the capacitor voltage. Record it in the space provided below:

E_C = ___________ volts

24. While you observe the AC voltage on your meter, slowly rotate the frequency dial on the generator in the clockwise direction. This increases the output frequency of the generator. Does the capacitor voltage increase or decrease? ___________

25. The voltage drop across the capacitor in this series RC circuit is directly proportional to the value of the capacitive reactance in the circuit. Therefore, you should conclude that increasing the frequency of the applied AC signal causes the capacitive reactance to ___________. In a similar manner, decreasing the frequency causes the reactance to ___________.

26. Switch the Trainer off and remove the circuit components from the Trainer.

Discussion

In steps 21 and 22 you observed the effect on the capacitive reactance when you changed the capacitance in a circuit with a fixed frequency. When used the data you accumulated in previous steps, you saw that increasing the capacitance in the circuit caused the reactance to decrease. When capacitance decreases, the reactance increases. Clearly then, reactance is inversely proportional to the capacitance. Increasing the reactance also increases impedance which decreases the circuit current. Decreasing the reactance, decreases the impedance and increases the current.

In steps 23 through 25, you demonstrated the effect that changing frequency has on the circuit reactance. You did this by measuring the voltage across a capacitor in a series RC circuit and then changing the frequency. Increasing the frequency causes the voltage across the capacitor to decrease. Since the voltage across the capacitor is proportional to the value of the capacitive reactance, the decrease in voltage indicates a decreasing reactance. In other words, as you rotate the generator dial to increase the frequency, the capacitor voltage and the capacitive reactance decrease. Rotating the frequency dial in the counterclockwise direction decreases the frequency and causes the voltage across the capacitor to rise. Decreasing the frequency then causes the reactance to increase. This demonstrates that the reactance is inversely proportional to frequency.

EXPERIMENT 4

Lissajous Patterns and Phase Angle

OBJECTIVES: *To identify Lissajous patterns.*

To determine the phase angle of Lissajous patterns displayed on an oscilloscope.

To observe characteristic wave patterns and the effects of increasing frequency and resistance on these wave shapes.

To demonstrate how an oscilloscope can provide a Lissajous pattern for evaluation of a graphic representation of phase and frequency.

Material Required

Heathkit Analog Trainer
Oscilloscope
1 — .1 μF capacitor
1 — 100 Ω, 1/2-watt resistor (brown-black-brown)
1 — 1 kΩ, 1/2-watt resistor (brown-black-red)
1 — 4.7 kΩ, 1/2-watt resistor (yellow-violet-red)

Introduction

In the first part of this experiment, you will construct a series RC circuit and measure the phase shift across the capacitor as compared to the input signal. This shift will be somewhere between 0° and 90°. In the second part of the experiment, you will vary both the resistance of the circuit and the frequency of the applied signal, and observe their effects on the phase shift within the circuit.

Procedure

1. Turn on your Trainer and oscilloscope.

2. Use the procedure you learned in steps 1 through 13 of Experiment 2 to setup your oscilloscope.

3. Set each VOLTS/DIV control to .5V andits variable to CAL.

4. Adjust the Trainer Generator section for a sine wave with a frequency of 2 kHz. Use your oscilloscope to observe the sine wave as you adjust the frequency.

   Remember, at 2 kHz, one cycle of the waveform is 500 μs long. Therefore, if you set the scope sweep time for 100 μ/cm (.1 ms/cm), one cycle should be 5 centimeters long. By stretching one cycle over 5 centimeters, you can set the frequency more accurately than if you had the sweep time set for 500 s/cm, which gives you one cycle-per-centimeter.

5. Switch the Trainer off and construct the circuit shown in Figure 3-35.

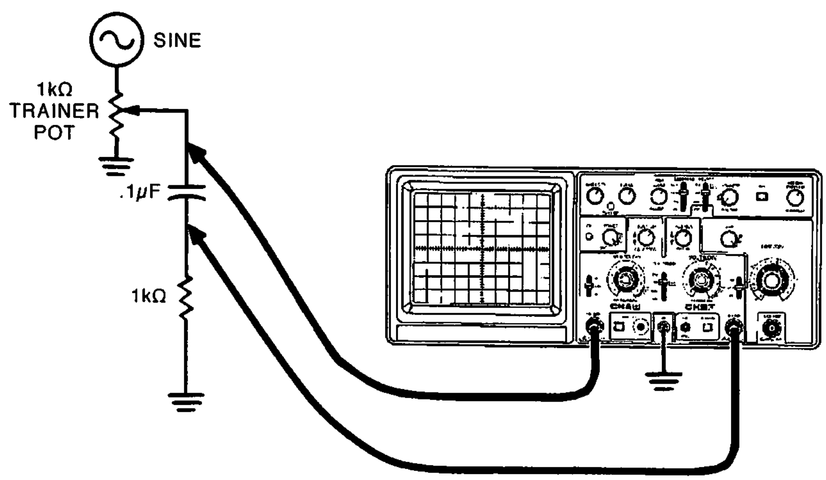


Figure 3-35

6. Select the X-Y mode of operation on your oscilloscope.

   As in the last part of Experiment 2, the Channel B vertical input is used in place of the normal scope time base so you can observe Lissajous patterns on the display.

7. Center the 1 kilohm pot on the Trainer and switch the Trainer on.

8. Use the HORIZONTAL and Channel B's VERTICAL POSITION controls on the scope to center the Lissajous pattern on the display.

9. Adjust the 1 kilohm pot on the Trainer, and the CHANNEL A VOLTS/DIV range switch and its VARIABLE control on the scope to adjust the size and angle of the pattern until it is 6 cm wide and 6 cm high, as shown in Figure 3-36.

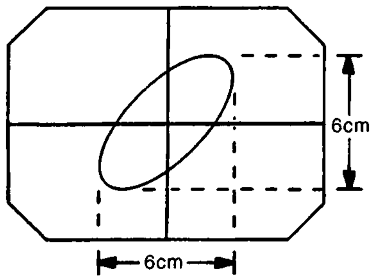


Figure 3-36

10. Make sure the waveform is still centered when you finish adjusting the size and angle of the Lissajous pattern.

11. Now, mathematically calculate the phase shift in the circuit that you constructed. The circuit resistance is 1000 ohms, capacitance is .1 μF, and input signal frequency is 2 kHz.

The phase angle is ___________ degrees.

12. On your oscilloscope, count the number of minor (smaller) divisions between points A and B as shown in Figure 3-37.

A-to-B = ___________ divisions.

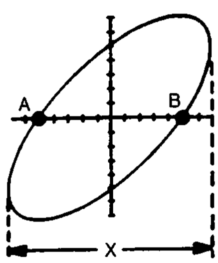


Figure 3-37

13. Count the number of minor (smaller) divisions for measurement X as shown in Figure 3-37.

X = __________ divisions.

14. With these two measurements, it is now possible to calculate the sine of the phase angle. You can use this formula:

$$\sin \theta = \frac{AB}{X}$$

Now insert your values and determine the sine of the phase angle.

$\sin \theta =$ __________

15. Find the angle in Appendix C of this unit.

Phase Shift = __________ degrees.

Discussion

The two signals that you used in this portion of the experiment were taken from different points in the circuit. The signal to the CHANNEL A INPUT of the oscilloscope was taken immediately at the input to the circuit. The signal to the CHANNEL B INPUT was taken from a point after the position of the capacitor in the circuit. Since the capacitor is positioned between these two points, there is a phase difference between the two signals. This difference depends upon the amount of capacitive reactance and the amount of resistance in the circuit.

The resistance of the circuit is 1000 ohms. At 2000 Hz, the .1 μF capacitor has a capacitive reactance of approximately 796 ohms. The vector diagram for this circuit is shown in Figure 3-38. With the trigonometric formula, you find:

$$\tan \theta = \frac{O}{A} = \frac{796}{1000} = .796$$

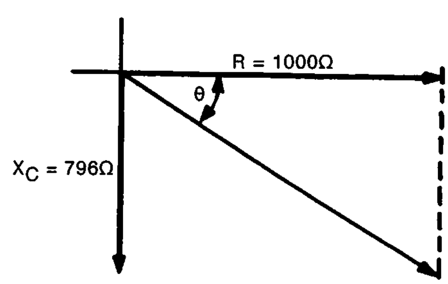


Figure 3-38

When you check the table in Appendix C, you will find that the phase shift is somewhere between 38° and 39°.

In steps 11 through 15 of the experiment, you used the oscilloscope to calculate the phase shift within the circuit. The number of minor divisions between points A and B is divided by the total number of minor divisions that the pattern spans. According to our calculations:

$$\sin = \frac{AB}{X} = \frac{19}{30} = .633$$

Again, checking the table in Appendix C, you find that the phase shift is about 39°.

Now, it is necessary to clarify one point. Your results with the oscilloscope may vary quite a bit from the results you obtained when you used trigonometric calculations. Bear in mind that the results with the scope presentation are affected by a number of things that are, for the most part, beyond your control.

First, the capacitor may not be exactly .1 µF Remember, there is a tolerance of +5%, and this can induce some error. By the same token, the 1000 ohm resistor also has a +5% tolerance.

Next, the oscilloscope itself can induce a small amount of error, and as you learned in Experiment 2, the scope probe can affect the phase of the signal.

Finally, you used visual estimates to gain the data for the calculation. The care that you use in counting the minor divisions can have a great effect on the eventual answer.

As you can see, the oscilloscope is not the perfect method to calculate phase shift, but it is a very useful tool in arriving at an approximate 10% value. When you take all of this into consideration, if your answer is within 10% of the mathematically-computed phase shift, you have performed the experiment correctly.

Procedure (Continued)

16. With a pencil, mark the position of the Trainer Generator frequency control on the front of the Trainer so you can return the control to its calibrated 2 kHz position in a later step.

17. Now, adjust the Trainer Generator frequency to approximately 200 Hz.

18. Center the resulting Lissajous pattern on your oscilloscope, and draw the shape of this pattern on the graph in Figure 3-39A on the next page.

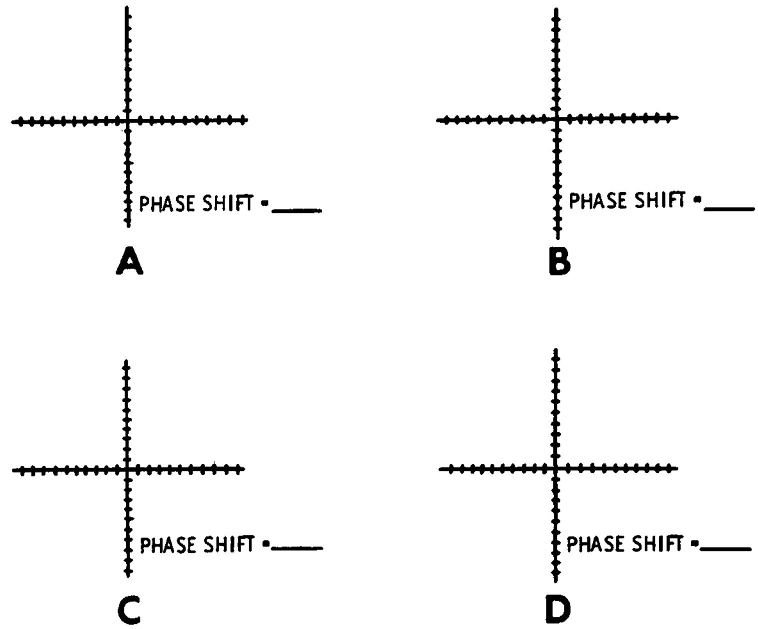


Figure 3-39

19. Use the method described in the previous section of this experiment to calculate the phase shift of the circuit at this new frequency, and put your answer in the space provided in Figure 3-39A.

20. Now, adjust the Trainer Generator frequency to approximately 20 kHz. Then, repeat steps 18 and 19 and record your findings in Figure 3-39B.

21. Return the Trainer frequency to 2 kHz.

22. Switch the Trainer off and replace the 1000 ohm resistor in the circuit with a 100 ohm resistor.

23. Switch the Trainer on and record your findings in Figure 3-39C.

24. Switch the Trainer off and replace the 100 ohm resistor in the circuit with a 4700 ohm resistor.

25. Switch the Trainer on and record your findings in Figure 3-39D.

26. Switch the Trainer and oscilloscope off and remove the circuit components.

Discussion

The illustrations shown in Figure 3-40 represent typical results that were arrived at for this portion of the experiment. Your results may vary somewhat from these.

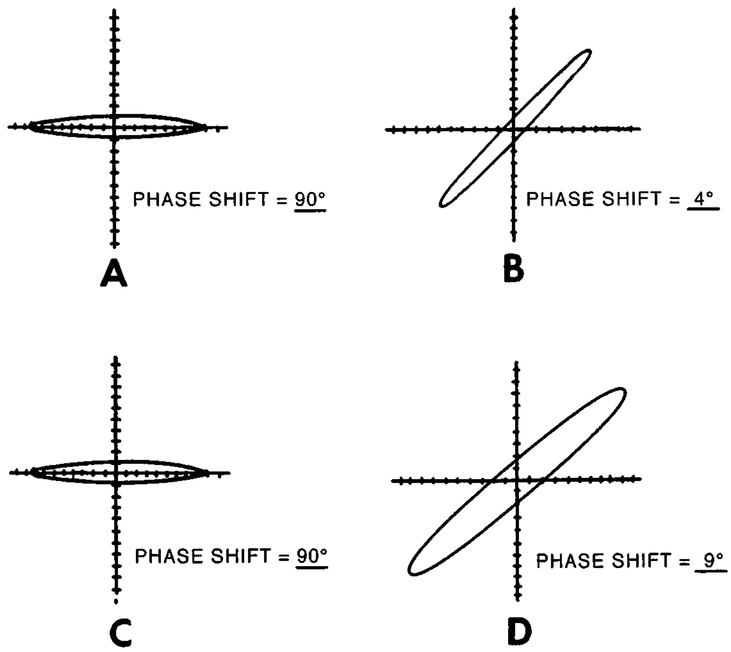


Figure 3-40

When you decreased the output frequency of the Generator in step 17, the shape of the pattern changed significantly. This occurs because, as the frequency of the signal decreases, the capacitive reactance of the circuit increases. Mathematically, the following equation predicts this:

$$X_C = \frac{1}{2\pi fC}$$

As capacitive reactance increases, the phase shift increases. The calculation with the Lissajous pattern places the phase shift at about 90°. This is not mathematically accurate, but it is close enough for a good approximation.

In step 20, you increased the output frequency of the Generator. When this occurs, capacitive reactance decreases and the phase shift also decreases. Again, Figure 3-40B represents the approximate pattern and phase shift.

In step 23, the resistance of the circuit decreased to 100 ohms. This results in a circuit whose operation is dominated by the capacitor. The Lissajous pattern is almost a straight vertical line. With little resistance in the circuit, the phase shift is about 90°.

Finally, in step 25, the resistance increased to 4700 ohms. As the circuit resistance increases, the phase angle decreases, because the ratio of the capacitive reactance to the resistance decreases. Remember, this ratio:

$$\frac{X_C}{R}$$

is equal to the tangent of the angle theta. When you check the functions in the table in Appendix C, you find that the angle decreased to some point near 9°, as shown in Figure 3-40D.

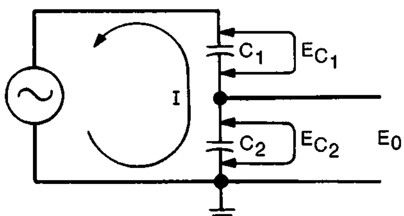
As you can see, a change in either the resistance or the input frequency to an RC circuit results in a change in the phase angle of the circuit.

APPLICATIONS OF CAPACITIVE CIRCUITS

In this section you will learn some of the more important applications of capacitors in AC circuits. While capacitors are often used alone, usually they are combined with resistors or other components to form RC networks. Such networks have many practical applications. Some of the applications are as AC voltage dividers, filters, decouplers, phase shifters, and coupling networks. Each of these applications is discussed in the text.

Capacitive Voltage Dividers

A capacitive voltage divider is a series capacitive circuit whose output is a fraction of its input. Figure 3-41 shows a simple capacitive voltage divider which consists of two capacitors, C_1, and C_2 in series. The input voltage is connected across both capacitors, but the output voltage is taken only across capacitor C_2.



$$E_C = \frac{E_i \times C_2}{XC_1 + XC_2}$$

Figure 3-41
A capacitive voltage divider.

The current flowing in the series circuit produces a voltage drop across each capacitive reactance. The sum of the capacitive voltage drops equals the input voltage. This shown in the expression:

$$E_I = E_{C1} + E_{C2}$$

In this application, the output voltage is equal to the voltage across capacitor C_2.

$$E_O = E_{C2}$$

The amount of voltage developed across each capacitor depends upon the current in the circuit and the capacitive reactance. According to Ohm's Law, the output voltage is:

$$E_O = E_{C2} \text{ or } I \times X_{C2}$$

The voltage drops across the capacitors in the circuit are in proportion to their capacitive reactances. The greater the capacitive reactance, the greater the voltage drop across that capacitor. Keep in mind that the reactance is a function of the size of the capacitor and the frequency of the applied voltage. Capacitive reactance is inversely proportional to both frequency and capacitance.

The output voltage is expressed in terms of the input voltage and the capacitive reactances, like this:

$$E_O = \frac{X_{C2}}{X_{C1} + X_{C2}} (E_i)$$

As you can see from this expression, the output voltage equals the input voltage multiplied by the ratio of the reactance of C_2 to the sum of the individual reactances. This ratio is referred to as the voltage divider ratio. It is the same ratio that you use to calculate voltage division in series resistive circuits. The only difference is that capacitive reactance replaces resistance in the equation.

You can also express the output voltage in terms of the capacitor values rather than the reactances. The formula below gives this relationship. Note that the output voltage is directly proportional to the voltage division ratio which is the ratio of C_1 to the sum of C_1 and C_2.

$$E_O = \frac{C_1}{C_1 + C_2} (E_i)$$

An interesting characteristic of a capacitive voltage divider is that the voltage division ratio is not affected by frequency. Even though the frequency causes the reactances to change, the reactances change together and the voltage division ratio remains constant. This is because as capacitive reactance changes as frequency changes, the circuit changes so that the product (IX_C) remains the same.

Another interesting characteristic of a purely capacitive voltage divider is that no phase shift occurs between the input and the output. The current in this circuit leads the applied voltage, but the voltage across the output capacitor is in phase with the input voltage. Changing the frequency has no effect on this characteristic.

You can often find capacitive voltage dividers in high frequency amplifier circuits. Certain types of oscillators use capacitive voltage dividers. To make the output voltage from a capacitive voltage divider variable, make either C_1, or C_2 a variable capacitor. You can adjust the output voltage by changing the ratio of capacitance.

RC Filters

A filter is a frequency-discriminating circuit. Filters greatly attenuate some frequencies while they allow others to pass with virtually no opposition. Filters are frequency selective because they pass some frequencies and attempt to block other frequencies.

Two of the most common types of filters in electronic circuits are the low-pass filter and the hi-pass filter. A low-pass filter allows low frequency signals to pass from the input to the output with little or no opposition (attenuation). In low-pass filter circuits, high frequencies are greatly attenuated by shunting them to ground. A frequency known as the cut-off frequency, F_{CO} is the general dividing line between those frequencies that are passed and those that are attenuated.

A high-pass filter is the opposite of a low pass filter. The high-pass filter permits frequencies above the cut-off frequency to pass. Frequencies below the cut-off point are greatly attenuated.

You can use simple RC networks as low and high-pass filters. Such circuits are able to perform a frequency selective function because their reactance changes with frequency.

LOW-PASS FILTER

The simplest form of a low-pass filter is shown in Figure 3-42A. It consists of a resistor and capacitor connected in series across an input voltage. The output voltage is taken across the capacitor. Assume that the input voltage has a fixed rms value, but that its frequency can be varied.

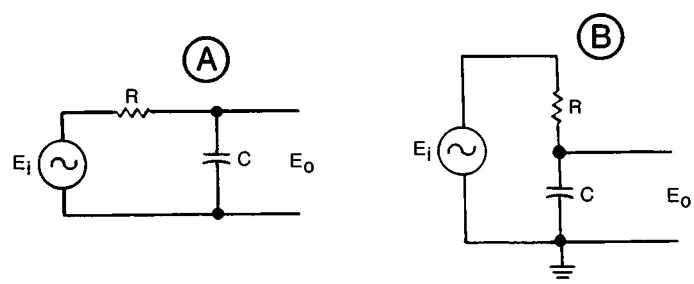


Figure 3-42
RC low-pass filter.

The best way to understand the operation of the low-pass filter is to look at the circuit as a voltage divider. The input voltage is applied across the resistor and capacitor in series, and the output voltage is taken across the capacitor. The voltage division ratio depends upon the sizes of the resistance and the capacitive reactance. The value of the resistance remains constant, of course, but the value of the capacitive reactance changes as the input frequency changes.

At very low input frequencies, the capacitive reactance is very high. If the reactance is high compared to the resistance, most of the input voltage is dropped across the capacitor. As the input frequency increases, the capacitive reactance decreases. This means that less voltage is dropped across the capacitor and more across the resistor as the frequency increases.

For this reason, the output voltage begins to drop off as frequency increases. At very high frequencies, capacitive reactance is very low. When capacitive reactance is significantly lower than the resistor's value, very little voltage will appear at the output terminals (across the capacitor).

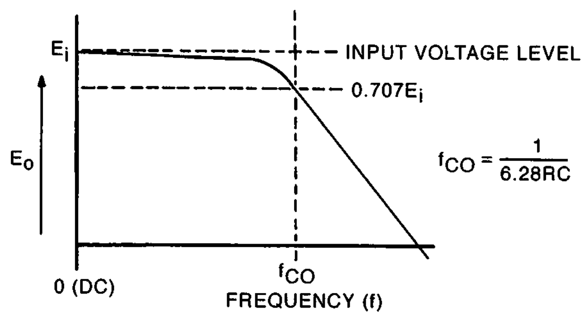


Figure 3-43
Frequency response of an RC low-pass filter.

The frequency response curve shown in Figure 3-43 illustrates this effect. This curve shows the amount of output voltage with respect to frequency. On the left-hand side of the curve, at very low frequencies, the output voltage is nearly equal

to the input voltage. In fact, with a frequency of 0 Hz or DC, the capacitor offers maximum opposition, and the output voltage equals the input voltage. As the frequency increases, the capacitive reactance begins to decrease. The output voltage then begins to drop off. After the cut-off frequency is reached, the output voltage drops off at a constant rate. At the cut-off frequency, the output voltage is approximately 70.7% of the input voltage or $E_O = .707\ E_i$. The cut-off frequency is a function of the resistor and the capacitor values and is expressed by the equation:

$$f_{CO} = \frac{1}{2\pi RC} = \frac{1}{6.28\ RC}$$

where R is in ohms and C is in farads.

To simplify the formula, solve for 1/6.28 and express C in microfarads:

$$f_{CO} = \frac{159200}{RC}$$

For example, the cut-off frequency of a circuit with a 10 k ohm resistor and .01 microfarad capacitor is:

$$R = 10\ \text{k ohm} = 10{,}000$$
$$C = .01\ \mu F$$

$$f_{CO} = \frac{159200}{10000\ (.01)} = 1592\ \text{Hz}$$

An important thing to note about an RC low-pass filter is that while the circuit is frequency selective, the selectivity is very gradual. The output is not sharply defined at the cut-off frequency. Higher frequencies are only attenuated, not cut out completely. In other words, the low-pass filter does pass frequencies higher than the cut-off frequency, but they are more greatly attenuated than those frequencies below the cut off point. Despite this imperfection in RC low-pass filters, these circuits are still very useful. The cut-off point is defined as those frequencies that cause less than the effective voltage to be developed (coupled) to the output.

HIGH-PASS FILTER

A simple RC high-pass filter is shown in Figure 3-44A. Like the low-pass filter, it consists of a resistor and a capacitor connected in series to the input voltage. In the high-pass filter, however, the output voltage is taken across the resistor. In Figure 3-33B, the circuit is drawn as a voltage divider.

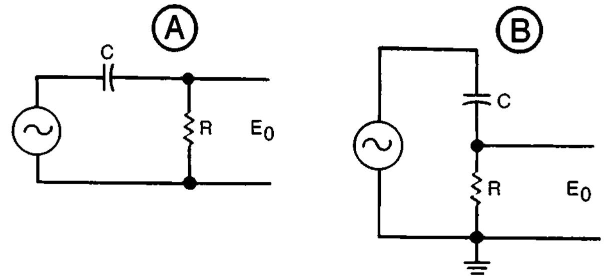


Figure 3-44
RC high-pass filter.

At very high input frequencies, the capacitive reactance is very low. When it is low compared to the resistance, little voltage is dropped across it. At high frequencies, most of the input voltage is dropped across the resistor. As frequency decreases, capacitive reactance increases. More and more voltage is dropped across the capacitance reactance and less across the resistor. When frequency decreases, the output voltage also decreases. The decrease is gradual at first, but at the cut-off frequency, the attenuation becomes more pronounced and the output voltage drops at a constant rate as the frequency decreases.

Figure 3-45 shows the frequency response curve of an RC high-pass filter. Note that at high frequencies the output voltage is nearly equal to the input voltage. As the frequency decreases, the output voltage begins to decrease. At the cut-off frequency, the output voltage is approximately 70. 7% of the input voltage. Below the cut-off frequency, attenuation increases and the output voltage drops accordingly.

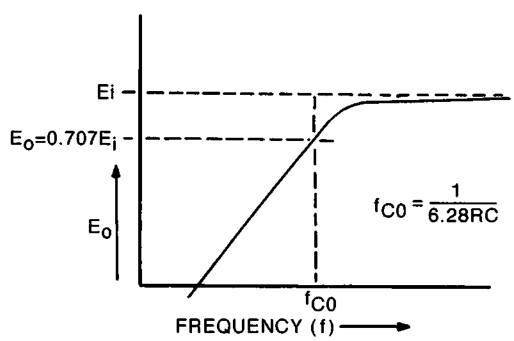


Figure 3-45
Frequency response of an
RC high-pass filter.

As in the low-pass filter, the cut-off frequency is a function of the resistor and capacitor values. The same expression you use to compute the cut-off frequency of a low-pass filter applies to the high-pass filter.

$$f_{CO} = \frac{159200}{RC}$$

Where:

R is in ohms
C is in μF
F_{CO} is in Hz

Circuits Combining AC and DC

Many electronic circuits operate with a combination of both AC and DC voltages. To these circuits, the applied voltage appears to be a DC voltage, such as a battery, connected in series with an AC generator. The result is a DC level (reference) on which an AC signal is superimposed. In this case, you can say that the AC rides on the DC. The zero line of the sine wave signal coincides with the DC voltage level. RC networks are commonly used with such AC/DC source voltages.

DECOUPLING NETWORK

Figure 3-46A shows one application of an RC circuit with an AC/DC source. The RC circuit is connected as a low-pass filter. The capacitor charges to the value of the DC voltage as indicated by the polarity shown. The sine wave voltage causes the charge on the capacitor to vary above and below the DC value by an amount equal to the peak value of the AC. Figure 3-46B shows the voltage across the capacitor. The combination voltage is often called pulsating DC. The composite voltage is still DC because it never goes negative. In this example, you can assume the frequency of the AC voltage to be lower than the cut-off frequency of the RC low-pass network. When the frequency of the AC input is higher than the cut-off frequency of the RC network, the output amplitude is greatly attenuated.

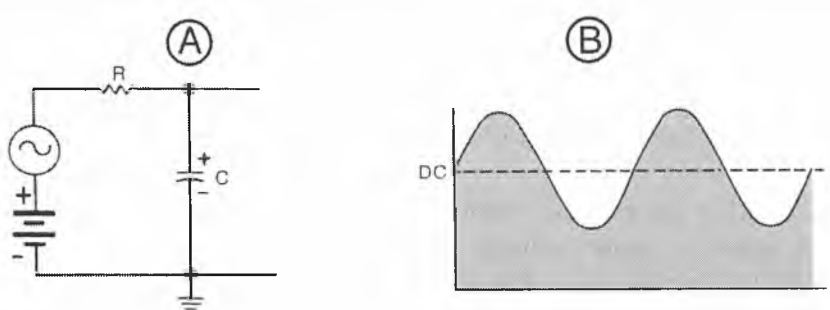


Figure 3-46
An RC decoupling network (A)
and the output waveform (B).

One of the more common applications for the low-pass RC network shown in Figure 3-46A is decoupling. Decoupling refers to the process of allowing a desired DC voltage to appear between given points, while at the same time eliminating or minimizing the AC at that point. In many electronic circuits, the DC voltage operates the equipment. AC signals in the form of oscillations, noise, and transient spikes sometimes appear as though they are connected in series with the DC supply voltage. An RC low-pass filter eliminates this unwanted AC. If you make the cut-off frequency of the RC network low enough, most or all of the undesired AC signals are filtered out, which leaves only the desired DC to develop across the capacitor.

COUPLING NETWORK

Another application of an RC circuit with AC/DC is shown in Figure 3-47. The source voltage is a combination of both AC and DC signals. This source is applied across a series RC network. However, in this application, the output is taken across the resistor. In other words, the RC network is used as a high-pass filter. The capacitor charges to the applied DC voltage. Once it charges, no further DC current flows in the circuit. Therefore, no DC appears across the output resistance. Instead, only the AC voltage appears as an output.

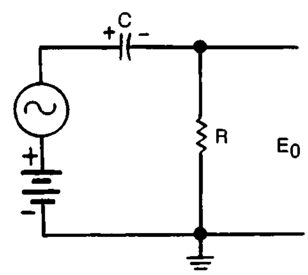


Figure 3-47
An RC coupling network.

The sine wave source causes the capacitor to charge and discharge at the AC rate. This creates current flow in the resistor, which appears at the output in the form of an AC voltage. In this application, only the AC signal appears at the output. The cut-off frequency of the RC network is adjusted so that it is low enough to permit the AC input to pass without noticeable attenuation.

This circuit is known as a coupling network. It is widely used to couple AC signals from one point to another while it blocks DC voltages. The capacitor prevents DC currents from flowing to the output. You must take care when you select the resistor and capacitor values. Due to the high-pass filter effect, you should choose their values so that the cut-off frequency permits passage of the desired AC signal with little or no attenuation.

For a circuit to be an effective coupling circuit, the RC time constant should be a minimum of 10 times the period of the waveform being coupled. Under this condition, the capacitor does not charge and discharge at the rate that the AC signal varies. Instead it charges and couples the AC signal with a minimum of distortion. The longer the RC time constant, the closer the reproduction of the input AC signal in the output.

Phase Shift Networks

You can also use RC networks for phase shifting. This is where the phase of an output sine wave signal from a circuit changed with respect to its input sine wave.

Phase shifting may be used for a number of reasons. Sometimes it is used to correct an unwanted phase shift that has been introduced by another component. In other applications, the phase shifting so you can compare succeeding signals can be compared for magnitude and frequency. No matter what the application, since a capacitor causes the current in the circuit to lead the applied voltage, you can use RC networks to shift the phase of a signal.

Figure 3-48 shows the two most commonly used phase-shifting configurations. In Figure 3-48A, the input signal is applied across the RC combination and the output is taken across the resistor. The current in the circuit leads the applied voltage by some phase angle between 0° and 90° degrees, depending upon resistor and capacitor values and the frequency of the applied signal.

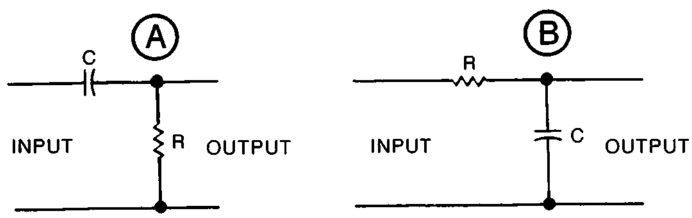


Figure 3-48
Basic RC phase shift networks (A) leading output, (B) lagging output.

The voltage across the resistor is in phase with the current that causes it. Because the current leads the applied voltage in the circuit, the voltage developed across the resistor, by the leading current, also leads the applied voltage. Therefore, the output voltage leads the input voltage. This relationship between input and output voltage is shown in Figure 3-49A on the next page.

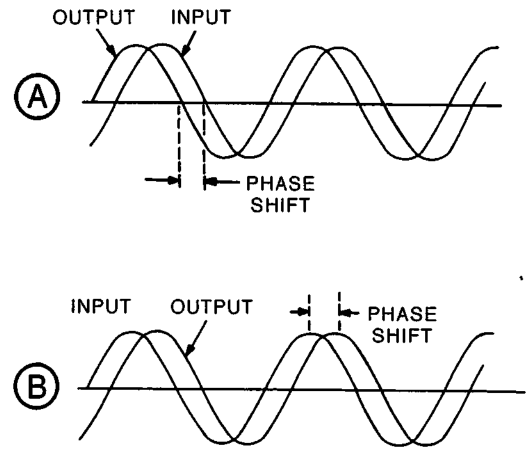


Figure 3-49
Phase shift in a series RC circuit (A) leading output, (B) lagging output.

In the phase shift circuit shown in Figure 3-48B, the output voltage is taken across the capacitor. Again, current leads the applied voltage in the circuit. In this case, however, because the output is taken across the capacitor, the phase shift is different. Now, the voltage at the output lags the input voltage by some phase angle between 0° and 90°. This is shown in Figure 3-49B.

Note that in both circuits shown in Figure 3-48 the comparison is made between the input and output voltages. Circuit A produces a voltage lead and circuit B produces a voltage lag. However, in both circuits, because they are capacitive in nature, the current through the circuit leads the applied voltage.

These elementary RC networks are used when only small amounts of phase shift are required. When a phase shift of greater than 60° is needed, other phase shifting techniques are usually used. The reason for this is that phase shifting networks also act as voltage dividers. As the phase shift across these networks approaches 90°, the capacitor drops a progressively larger percentage of the applied voltage. In addition, the impedance of the circuit itself becomes a problem.

One way to obtain a greater phase shift is to cascade the simple RC network shown in Figure 3-48, so that the output of one network is connected to the input of another network. This creates a total phase shift that is equal to the sum of the individual phase shifts. For example, if three 45° phase shift networks are cascaded as shown in Figure 3-50, the total phase shift is 3 × 45° or 135°. In this case, the output voltage leads the input voltage by 135°.

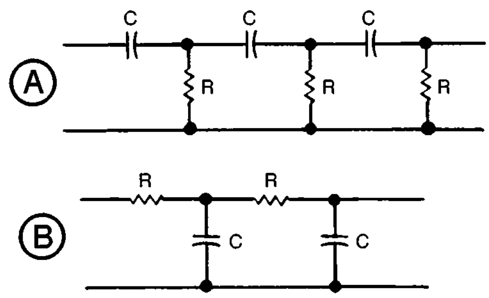


Figure 3-50
Cascade RC phase shift networks.

To achieve a lagging phase shift greater than is obtainable with a single RC network, you can use the circuit of Figure 3-50B. Here, two networks are cascaded. For example, if each network provided a phase shift of 45°, the output will lag the input by a total of 90°.

While cascaded RC networks can provide any degree of phase shift that you desire, keep in mind that each RC section acts as a voltage divider. This means that the output voltage is much lower than the input voltage. Where such networks are used, amplifiers are generally required to offset the attenuation and bring the output voltage back to a usable level.

Finally, it is important to note that the phase shift produced by an RC network is a function of the resistor and capacitor values. This phase shift is valid for only a single frequency. If an RC network is designed to produce a desired phase shift for one frequency, the amount of phase shift produced by that network at another frequency is different. The reason for this is simple. If the frequency changes, the capacitive reactance also changes, and changing the reactance changes the phase angle.

Programmed Review

102. A capacitive voltage divider uses two or more capacitors in series to generate an output that is some fraction of the input voltage. This means that the output is always _________ than the input.

103. (less) The output is always some fraction of the input. This fraction is called the __________ __________ __________.

104. (voltage division ratio) To obtain the output voltage, you multiply the __________ __________ by this ratio.

105. (input voltage) The ratio is a function of the capacitor values. In a two-capacitor divider where the output is taken from C_2, the ratio is __________.

106. ($\frac{C_1}{C_1 + C_2}$) If $C_1 = .001\ \mu F$ and $C_2 = .004\ \mu F$, the ratio is ________.

107. (.2) If the input voltage is 7 volts, the output will be _________.

108. (1.4) A series RC circuit that passes low frequencies but attenuates high frequencies is called a __________-__________ __________.

109. (low-pass filter) In a low-pass filter, the input signal is applied across the resistor and capacitor and the output is taken from across the __________.

110. (capacitor) As the input frequency increases, X_C __________ and the output voltage __________.

111. (decreases, decreases) The frequency below which all signals pass with little or no attenuation is called the __________ frequency.

112. (cut-off) The cut-off frequency (f_{CO}) is a function of the ___________ and ___________ values.

113. (resistor, capacitor) The formula for the cut-off frequency is ___________ .

114. ($f_{CO} = \frac{1}{6.28\ RC}$ or $\frac{159200}{RC}$)

If R = 15 k ohms and C = .05 µF, f_{CO} = ___________ Hz.

115. (212) Frequencies ___________ (above/below) f_{CO} in a low pass filter will be greatly attenuated in a low-pass filter.

116. (above) A high-pass filter is an RC circuit where the output voltage is taken from across the ___________ .

117. (resistor) A high-pass filter greatly attenuates frequencies ___________ (above/below) the cut-off frequency.

118. (below) It passes frequencies above f_{CO} with little or no attenuation. You can compute the cut-off frequency with the formula ___________ .

119. ($f_{CO} = \frac{1}{6.28\ RC}$)

The cut-off frequency formula is the same for both low- and high-pass filters. If the input voltage to a high-pass filter is DC combined with AC, the output voltage will be _________ only.

120. (AC) The capacitor blocks the DC input and passes the AC, if the frequency of the AC signal is higher than the cut-off frequency. When a high-pass filter is used this way, it is called a ___________ circuit.

121. (coupling) The AC signal is coupled or passed by the circuit but any DC is blocked. When the input to a low-pass filter is DC and AC, the DC ___________ (does/does not) appear at the output.

122. (does) The output is taken from across the capacitor which charges to the DC input, so the DC does appear at the output. The AC also appears at the output if its frequency is ___________ cut-off frequency.
above/below

123. (below) But if the cut-off frequency is made very low, this circuit will attenuate most AC signals. It passes DC but eliminates AC. When used this way the low-pass filter is called a circuit.

124. (decoupling) When an RC circuit is used to introduce phase shift into a circuit it is called a ____________ ____________ .

125. (phase shifter) A single RC phase shifter can generate phase shifts between _________ and _________ degrees.

126. (0, 90) The output drops considerably as the phase shift approaches 90°. Phase shifters can be set up so that the output voltage occurs later in time than the input. This is referred to as a ___________ phase shifter.

127. (lagging) If the output occurs earlier than the input, it is called a ___________ phase shift.

128. (leading) An RC network can produce either leading or lagging outputs depending upon whether the output is taken from across the resistor or the capacitor. If the output is taken from across the resistor, the output will ___________ the input.

129. (lead) Taking the output from across the capacitor produces ___________ phase shift.

130. (lagging) To achieve phase shifts greater than 90°, RC networks can be ___________ .

131. (cascaded) When you connect one RC network to another, the phase shifts are additive. If each RC network in a three section phase shifter generates 55° of shift, the total shift is ___________ degrees.

132. (165 $3 \times 55° = 165°$)

EXPERIMENT 5

Capacitor Applications

OBJECTIVES: *To examine the properties of a capacitive voltage divider.*

To identify high-pass and low-pass RC filters.

To verify the characteristics of RC filters.

To compare the computed output voltage and cut-off frequency of an RC filter to the measured values.

Materials Required

Heathkit Analog Trainer
Oscilloscope
AC Voltmeter
1 — .001 µF capacitor
1 — .039 µF capacitor
1 — .1 µF capacitor
1 — .47 µF capacitor
1 — 4.7 kΩ, 1/2-watt resistor (yellow-violet-red)
1 — 47 kΩ, 1/2-watt resistor (yellow-violet-orange)

Procedure

1. Construct the experimental circuit shown in Figure 3-51. Connect the capacitors together on the main breadboarding area, then use hook-up wire to connect them to the 15 VAC 60 Hz line source and ground. You can use the oscilloscope or AC voltmeter to measure voltage in the following steps.

2. Use your AC voltmeter to measure the input voltage. The output of the line source on your Trainer is specified as 15-volts rms. However, you need to know the exact value in order to make the proper calculations in this experiment. The value of the output voltage depends upon the AC power line voltage in your area. Connect your voltmeter leads to the capacitors at the line source terminals to measure this voltage. Record your voltage in the space below:

E_i = __________ volts

3. Use the values in Figure 3-51 to compute the voltage division ratio. Record this value in the space below:

Voltage division ratio = ___________ .

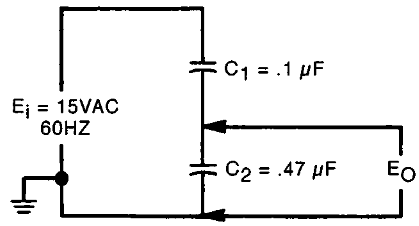


Figure 3-51
Experimental circuit: capacitive voltage divider.

4. Use the value of input voltage you obtained in step 2 to compute the output voltage you expect with the voltage division ratio computed in step 3 above. Record your expected output voltage in the space below:

E_O = ___________ volts.

5. Use your AC voltmeter to measure the voltage across C_2. This is the output voltage of the voltage divider. Record your measurement below:

E_O = ___________ volts.

How do your computed and actual measured values of output voltage compare? Explain any discrepancies. ______________________________

____

____

Discussion

The output of the capacitive voltage divider in Figure 3-51 is some fraction of the input voltage. This fraction is referred to as the voltage division ratio and is a function of the sizes of the capacitors in the circuit. The voltage division ratio for this circuit is:

$$\frac{C_1}{C_1 + C_2}$$

When you use the capacitor values in Figure 3-43, the voltage division ratio is:

$$\frac{C_1}{C_1 + C_2} = \frac{.1}{.1 + .47} = \frac{.1}{.57} = .175$$

To obtain the output voltage, multiply the voltage division ratio by the input voltage. Your input voltage should have measured approximately 15 volts rms or slightly more. When you multiply this input voltage by the voltage division ratio, you should have obtained the output voltage. A typical value of input voltage is 16 volts rms. With the voltage division ratio you computed above, the output voltage should be approximately $16 \times .175 = 2.8$ volts or very close to 3 volts. The value you measured in step 5 should correspond closely to this value. Component tolerance and measurement errors can cause some discrepancies, but your measured and computed values should be fairly close.

Procedure (continued)

6. Disconnect the voltage divider circuit. Then construct the experimental circuit shown in Figure 3-52. Connect the resistor and capacitor on the circuit breadboard. Use hook-up wire to connect the circuit to the output of the signal generator. Set the generator range switch to the LOW position and adjust the frequency dial to the 200 Hz position.

   This circuit is an RC filter. Study the circuit and determine which type it is. The circuit is a __________ pass filter.

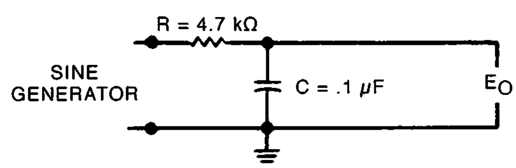


Figure 3-52
Experimental filter circuit, step 6.

7. Use the values of resistance and capacitance shown in Figure 3-52 to compute the cut-off frequency. Record your frequency below:

   F_{CO} = __________ Hz.

8. Turn on your Trainer. Use your AC voltmeter to measure the output voltage of the signal generator. Be sure you connect the ground lead of your voltmeter to the GND output terminal. Measure the voltage that is applied to the circuit where the 4.7 k ohm resistor connects to the SINE output. Record this voltage below:

$E_i =$ ____________ volts.

9. Determine the output voltage of the circuit at the cut-off frequency. To make this computation, use the input voltage you used in the previous step. Record the voltage at the cut-off frequency below:

$E_O\ (f_{CO}) =$ ____________ volts.

10. Connect your AC voltmeter across the .1 μF capacitor. Rotate the frequency dial on the generator in the clockwise direction until the voltmeter indicates the voltage you computed for the cut-off frequency. When you reach this voltage, stop turning the knob and note the approximate frequency from the dial. The generator frequency dial is only roughly calibrated, but you can estimate the frequency within several hundred Hertz. Record your estimate below:

$f_{CO} =$ ____________ Hz.

11. While you monitor the output voltage across the capacitor, continue to rotate the frequency dial in the clockwise direction. Note how the output voltage varies. Then complete the statement below:

As you increase the frequency, the output voltage ____________ .

Discussion

The circuit you constructed in step 6 is a low-pass filter. You can use the following expression to determine the cut-off frequency, which is a function of the resistor and capacitor values:

$$F_{CO} = \frac{159200}{RC}$$

When you use the values in Figure 3-52 to compute the cut-off frequency of this circuit, you found it to be:

$$F_{CO} = \frac{159200}{4700\ (.1)} = 338.7 \text{ Hz}$$

In step 7, you measured the input voltage to the circuit at approximately 200 Hz. Since this frequency is less than the calculated cut-off frequency, the attenuation of the circuit should be minimal. You then used this value to compute the output voltage at the cut-off frequency. As you recall, the output voltage is approximately 70% of the input voltage at some frequency below the cut-off point. The actual output voltage at the cut-off frequency is .707 times the input voltage at that lower frequency. If the input voltage to your circuit at the low input frequency is 5 volts, the output at the cut-off frequency will be $.707 \times 5 = 3.535$ volts.

Next you adjusted the frequency of the generator to produce the desired output voltage. You did this by increasing the output frequency of the generator. When the measured output voltage equaled the calculated value of the output voltage, the generator produced a signal at the cut-off frequency. When you read the dial, you should have been able to estimate the value of the cut-off frequency. This estimated value should have approximated your computed value.

Procedure (continued)

12. Disconnect the low-pass filter circuit. In its place, construct the circuit shown in Figure 3-53. As before, construct the resistor and capacitor on the breadboarding socket and connect it to the outputs of the generator. Study the circuit in Figure 3-53, and answer the statement below:

    The RC network shown in Figure 3-53 is a __________ pass filter.

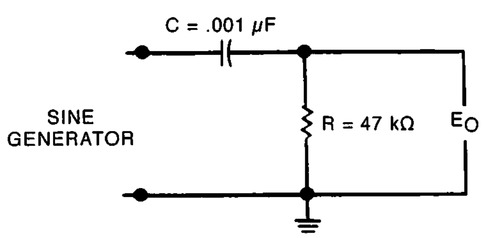


Figure 3-53
Experimental filter circuit, step 12.

13. Use the component values in Figure 3-53 to compute the cut-off frequency of the circuit. Record your value below:

    F_{CO} = __________ Hz.

14. Turn on your Trainer. Be sure that the generator range switch is in the LOW position. Turn the frequency dial to the 200 Hz position. Connect your AC voltmeter across the 47 kΩ resistor. You will measure the output voltage of the circuit as you vary the frequency. At this time, the output voltage from the circuit will be relatively low.

    Next, begin to rotate the frequency dial in the clockwise direction. Note the variation in output voltage. When you reach the 2 kHz position of the dial and make your observation, return the dial to the 200 Hz position. Then set the range switch on the generator to the HIGH position. Again note the output voltage on your AC voltmeter. Then rotate the dial in the clockwise direction to increase the frequency of the generator. After you complete this operation, complete the statement below:

    As the input frequency to the RC circuit is increased, the amplitude of the output voltage __________.

15. With the range switch on the generator in the HIGH position, rotate the frequency dial to the 20 kHz position. Use your AC voltmeter to measure the input voltage to the circuit. In other words, measure the voltage coming directly out of the generator circuit between the SINE and GND terminals. Record that input voltage in the space below:

    E_i = __________ volts.

16. Use the voltage you measured in the previous step as a reference to compute the output voltage of this filter circuit at the cut-off frequency. Record this value of voltage in the space below:

    E_O (f_{CO}) = __________ volts.

17. Connect your AC voltmeter to the output of the circuit (across the 47 kΩ resistor). Rotate the frequency dial in the counterclockwise direction until the voltmeter indicates the voltage you computed for the cut-off frequency. When you reach this voltage, note the dial setting. The dial gives you only an approximation of the cut-off frequency. Estimate as closely as possible and record your estimate below:

    f_{CO} = __________ Hz.

Discussion

The filter circuit that you constructed for these steps is a high-pass filter. You applied an AC signal from the generator in your trainer and monitored the output voltage. The initial frequency applied was very low, about 200 Hz. This frequency is well below the cut-off point, so the output voltage of the filter at this time is very low. As you increased the frequency, you should have noted an increase in the output voltage. As you varied the frequency dial from the 200 Hz to the 2 kHz position with the range switch set to LOW, you should have noted only a slight increase in the output voltage.

When you set the range switch to the HIGH position and continued to increase the frequency, you should have noted a marked increase in the output voltage. The output voltage should have begun to rise significantly. This indicated that you passed the cut-off frequency, which allowed most of the input voltage to reach the output. As you increased the frequency, the capacitive reactance decreased. This means that less voltage was dropped across the capacitor and more voltage appeared across the output resistor. This clearly indicates that the circuit passes high frequency signals and rejects low frequency signals.

However, when you adjusted the frequency control to the highest frequencies, you may have noticed that the voltage drop across the component decreased. This happens because the voltage output of the Trainer tends to decrease at the high end of either frequency range. If, however, you measure the voltages across the individual components in the circuit, you will find that the ratio of the voltage drops are consistent with the theoretical result of the experiment.

With the values in Figure 3-53, your calculated cut-off frequency is approximately 3387.2 Hz. The calculation is shown below.

$$F_{CO} = \frac{159200}{47000\,(.001)} = 3387.2 \text{ Hz}$$

Frequencies below this cut-off point are greatly attenuated, while frequencies above this point are passed with little or no opposition.

In step 16 you computed the output voltage for the cut-off frequency. This voltage could vary over a wide range, depending upon the specific output voltage of the generator in your Trainer. The output voltage at the cut-off frequency is .707 multiplied by the input voltage that you measured. You then adjusted the generator output frequency for this value of voltage. At that time, the frequency applied to the filter is the cut-off value. When you read that frequency from the dial, you should have found it to be close to the value calculated above.

UNIT EXAMINATION

The following multiple choice examination is designed to test your understanding of the material presented in this unit. Place a check beside the multiple choice answer (A, B, C, or D) that you feel is most correct. After you complete the examination, compare your answers with the correct ones that appear after the exam.

1. The unit of measurement for capacitance is the:

   A. ohm.
   B. farad.
   C. coulomb.
   D. henry.

2. Which of the following factors does not affect the value of a capacitor?

   A. plate area
   B. plate spacing
   C. plate thickness
   D. dielectric constant

3. The value of a .01 μF capacitor expressed in farads is:

   A. $.01 \times 10^{-6}$.
   B. $.01 \times 10^{6}$.
   C. $.01 \times 10^{12}$.
   D. $.01 \times 10^{-12}$.

4. A 100 pF capacitor expressed in microfarads is:

   A. .1 μF.
   B. .01 μF.
   C. .001 μF.
   D. .0001 μF.

5. The following three capacitors are connected in parallel. C_1 = 470 pF, C_2 = 750 pF, C_3 = .00033 μF. The total capacitance is:

   A. 1220.00033 pF.
   B. 1253 pF.
   C. 1550 pF.
   D. 4520 pF.

6. A .022 μF capacitor is connected in series with a .0047 μF capacitor. The total capacitance is:

   A. 3873 pF.
   B. 387.3 pF.
   C. .0267 μF.
   D. .03872 μF.

7. The total opposition to current flow in a purely capacitive AC circuit is called:

   A. resistance.
   B. reactance.
   C. impedance.

8. If the frequency of AC applied to a capacitor decreases, the capacitive reactance:

   A. increases.
   B. decreases.
   C. does not change.

9. Increasing the capacitance for a given frequency causes the reactance to:

   A. increase.
   B. decrease.
   C. remain the same.

10. Decreasing the applied voltage in a capacitive AC circuit causes the reactance to:

    A. increase.
    B. decrease.
    C. remain the same.

11. What is the reactance of a .05 μF capacitor at 400 Hz?

    A. 7960 ohms
    B. 15920 ohms
    C. 31840 ohms
    D. 63680 ohms

12. What value of capacitor has a reactance of 15 k ohms at 60 Hz?

    A. .001 77 µF
    B. .0177 µF
    C. .177 µF
    D. 1.77 µF

13. The total opposition to current flow in an RC circuit is:

    A. resistance.
    B. reactance.
    C. impedance.

14. What is the impedance of a series RC circuit whose resistance is 90 ohms and reactance is 120 ohms?

    A. 14.5 ohms
    B. 150 ohms
    C. 210 ohms
    D. 22500 ohms

15. The impedance of an RC circuit is 300 ohms. What is the current if 12 volts is applied?

    A. 25 milliamperes
    B. 36 milliamperes
    C. 40 milliamperes
    D. .4 amperes

16. What is the approximate phase shift in a series RC circuit with R = 1000 ohms and X_C = 810 ohms?

    A. 36°
    B. 39°
    C. 51°
    D. 54°

17. In a capacitive circuit, the applied voltage:

    A. is in phase with the current.
    B. leads the current.
    C. lags the current.

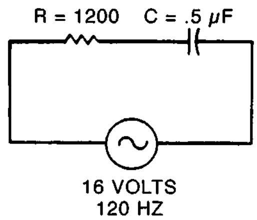


Figure 3-54
Circuit for exam questions.

18. Refer to the circuit in Figure 3-54. The impedance of this circuit is:

    A. 1906 ohms.
    B. 2653 ohms.
    C. 2912 ohms.
    D. 3853 ohms.

19. The true power dissipated in the circuit of Figure 3-54 is:

    A. 36 milliwatts.
    B. 66 milliwatts.
    C. 96 milliwatts.
    D. 213 milliwatts.

20. The approximate phase shift in the circuit of Figure 3-54 is:

    A. 24°.
    B. 34°.
    C. 66°.
    D. 76°.

21. The approximate cut-off frequency of the circuit in Figure 3-54 is:

    A. 65 Hz.
    B. 104 Hz.
    C. 133 Hz.
    D. 265 Hz.

22. The RC circuit that attenuates all frequencies above the cut-off frequency is called a:

    A. low-pass filter.
    B. high-pass filter.
    C. voltage divider.
    D. phase shifter.

23. The input voltage to a high-pass filter is 10 volts at 10 kHz. The cut-off frequency is 4 kHz. What is the approximate output voltage at the cut-off frequency?

A. 2.5 volts
B. 4 volts
C. 7 volts
D. 10 volts

24. An RC circuit has a resistance of 2 kΩ and a capacitance of .01592 μF. The frequency is 5 kHz. What is phase angle?

A. 32°
B. 45°
C. 56°
D. 81°

25. In the circuit described in question 24, what is f_{CO}?

A. 1 kHz
B. 2 kHz
C. 3 kHz
D. 5 kHz

EXAMINATION ANSWERS

1. B — farad.
2. C — plate thickness
3. A — $.01 \times 10^{-6}$. $.01\ \mu F = .01 \times .000001$ or $.01 \times 10^{-6}$ farads
4. D — $.0001\ \mu F$. $100\ pF = 100 \times 10^{-6} = .0001\mu F$
5. C — 1550 pF. $.00033\ \mu F = 330\ pF$. $470 + 750 + 330 = 1550\ pF$
6. A — 3873 pF.

$$C_T = \frac{.022\ (.0047)}{.022 + .0047} = \frac{.0001034}{.0267} = .003873\ \mu F \text{ or } 3873\ pF$$

7. B — reactance.
8. A — increases.
9. B — decrease.
10. C — remain the same. Changing the applied voltage in capacitive circuits does not affect the reactance. The reactance is a function of the frequency and capacitance only.
11. A — 7960 ohms

$$X_C = \frac{159200}{fC} = \frac{159200}{400\ (.05)} = 7960 \text{ ohms}$$

12. C — $.177\ \mu F$

$$C = \frac{159200}{fX_C} = \frac{159200}{60\ (15000)} = .177\ \mu F$$

13. C — impedance
14. B — 150 ohms

$$Z = \sqrt{R^2 + X_C{}^2} = \sqrt{90^2 + 120^2} = \sqrt{8100 + 14400} =$$
$$\sqrt{22500} = 150 \text{ ohms}$$

15. C — 40 milliamperes

$$I = \frac{E}{Z} = \frac{12}{300} = .04 \text{ amperes } = 40 \text{ milliamperes}$$

16. B — 39°

$$\tan\theta = \frac{X_C}{R} = \frac{810}{1000} = .81$$

17. C — lags the current. The applied voltage lags the current in a capacitive circuit which is another way of saying that the current leads the voltage.

18. C — 2912 ohms

$$X_C = \frac{159200}{FC} = \frac{159200}{120\,(.5)} = 2653.3 \text{ ohms}$$

$$Z = \sqrt{R^2 + X_C{}^2} = \sqrt{1200^2 + 2653.3^2} =$$

$$\sqrt{1440000 + 7039971} = \sqrt{\sqrt{8479971}} = 2912 \text{ ohms}$$

19. A — 36 milliwatts. The true power is that power dissipated in the resistor.

$$I = \frac{E}{Z} = \frac{16}{2912} = .0055 \text{ amperes}$$

$$P = I^2 R = (.0055)^2\, 1200 = .036 \text{ watts}$$

$$.036 \text{ watts} = 36 \text{ milliwatts}$$

20. C — 66° $\tan\theta = \frac{X_C}{R} = \frac{2653.3}{1200} = 2.21$

Therefore $\theta = 65.7°$ or about 66°

21. D — 265 Hz

$$f_{CO} = \frac{159200}{1200\,(.5)} = 265 \text{ Hz}$$

22. A — low-pass filter
23. C — 7 volts. The output voltage at the cut-off frequency is .707 times the input voltage or $.707 \times 10 = 7.07$ volts.
24. B — 45°

$$X_C = \frac{159200}{fC} = \frac{159200}{5000\,(.01592)} = 2000 \text{ ohms}$$

$$\tan\theta = \frac{X_C}{R} = \frac{2000}{2000} = 1$$

Therefore, $\theta = 45°$

25. D — 5 kHz

$$f_{CO} = \frac{159200}{RC} = \frac{159200}{2000\,(.01592)} = 5000 \text{ Hz} = 5 \text{ kHz}$$

Note concerning questions 24 and 25: In an RC circuit, $X_C = R$ at the cut-off frequency and the phase angle at that time is 45°.

APPENDIX A: SOLVING RIGHT TRIANGLES

This lesson describes a method you can use to solve right triangles. Right triangles are widely used in electronics to represent electrical quantities and solve problems that involve them. This lesson explains right triangles and gives you a simple method of dealing with them.

The material in this lesson is presented to you a step at a time. The information to be learned is divided into small pieces called frames. Each frame presents a key fact or idea. You are then immediately tested on this fact. You respond by filling in a blank to complete a statement. The correct answer is given in parentheses at the beginning of the next frame. As you read each frame, keep the frames below covered with a piece of paper. Begin now with frame 1.

1. A triangle is a three-sided geometric figure. See Figure A1. The three sides are labeled A, B, and C and form three angles which are called a, b, and c. The sum of the angles in any triangle is 180° or a + b + c = 180°.

   All triangles have ___________ sides and ___________ angles.

2. (three, three) The sum of the three angles is always ___________ degrees.

3. (180) One of the most commonly triangles you will encounter is the right triangle. A right triangle contains one 90° angle. Figure A2 shows a typical right triangle.

   A triangle with one 90° angle is called a ___________ triangle.

4. (right) In Figure A2, the right angle is identified by the letter ___________.

5. (c) If the right angle c has 90°, the sum of the other two angles (a + b) must be ________ degrees.

6. (90) In order for the sum of angles a and b to be 90°, each must be less than 90°. Any angle less than 90° is called an acute angle.

   An angle of 57° is an ___________ angle.

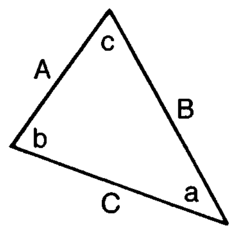


Figure A1

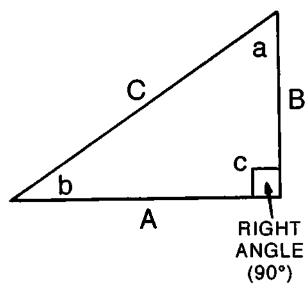


Figure A2

7. (acute) In a right triangle there are ___________ (how many) acute angles?

8. (two) Angle c in Figure A2 is a right angle, while angles a and b are acute angles.

In Figure A2, angle a = 35°. Angle b = ___________ degrees.

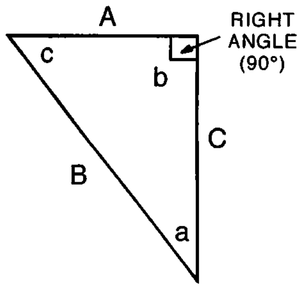


Figure A3

9. (55) If c = 90°, a + b must equal 90°. Therefore, b = (90 – a) or 90° – 35° = 55°. Remember that all triangles have a total of 180° or a + b + c = 180°.

The sides that form the right angle in Figure A2 are ___________ and ___________.

10. (A, B) Sides A and B meet at a right angle. Therefore, side A is perpendicular to side B.

In the right triangle of Figure A3, which two sides are perpendicular? ___________.

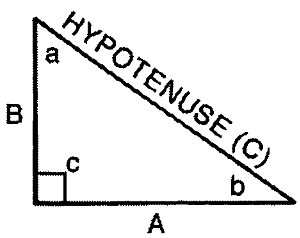


Figure A4

11. (A and C) Yes, sides A and C form a 90° angle so they are perpendicular. Note that the right angle is always identified by the small square in the corner that is formed by the perpendicular sides.

The right angle in Figure A3 is designated by the letter ___________.

12. (b) The side of the triangle that is directly opposite the right angle is called the hypotenuse. See Figure A4. The hypotenuse is side C.

Study Figure A5. Which side is the hypotenuse? ___________.

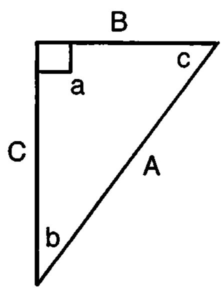


Figure A5

13. (A) The hypotenuse is always the side opposite the right angle. The lengths of the sides of a right triangle are related by a unique relationship. This relationship is expressed by the formula below:

$$C = \sqrt{A^2 + B^2}$$

This formula says that the length of the hypotenuse (side C) equals the square root of the sum of the squares of the other two sides.

Sketch a right triangle that illustrates this relationship. Identify all sides and angles. Label the hypotenuse.

14. (see Figure A6) With this formula, you can calculate the length of the hypotenuse if you know the lengths of the other two sides. For example, if side A = 3 inches and side B = 4 inches, what is the length of the hypotenuse? The solution is given below:

$$C = \sqrt{A^2 + B^2}$$
$$C = \sqrt{(3)^2 + (4)^2}$$
$$C = \sqrt{9 + 16}$$
$$C = \sqrt{25}$$
$$C = 5$$

NOTE: The expression A^2 means to square A or multiply A by itself. $A^2 = A \times A$. If A = 3 then $A^2 = 3 \times 3 = 9$. The square root of a number is another number that when it is multiplied by itself gives the original number. It is the opposite of finding the square of a number. For example, the square root of 9 is $\sqrt{9} = 3$ since $3 \times 3 = 9$. You can find the square root of a number by the longhand process you learned in school. But the easiest way to find the square root is to use an electronic calculator with the square root function ($\sqrt{X}$).

What is the length of the hypotenuse of a right triangle with sides of A = 6 and B = 9? C = ___________.

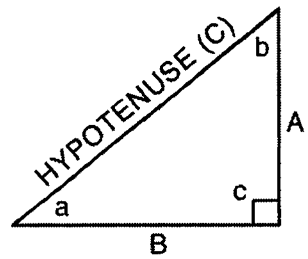


Figure A6

15. (10.8) The solution to the problem is as given below:

$$C = \sqrt{A^2 + B^2}$$
$$C = \sqrt{(6)^2 + (9)^2}$$
$$C = \sqrt{36 + 81}$$
$$C = \sqrt{117}$$
$$C = 10.8$$

You can use basic algebra to rearrange the basic formula so that you can find the length of a side if you know the length of the hypotenuse and the length of the other side. The formulas for this are:

$$A = \sqrt{C^2 - B^2}$$

$$B = \sqrt{C^2 - A^2}$$

The letter ___________ designates the hypotenuse.

16. (C) The hypotenuse is usually called C, although there are no set rules about this. For all of the examples given here, Figure A6 applies. The hypotenuse is called C.

If the hypotenuse is 14 and side A = 6, what is side B? B = ________.

17. (12 .65) See the solution below:

$$B = \sqrt{C^2 - A^2}$$

$$B = \sqrt{(14)^2 - (6)^2}$$

$$B = \sqrt{196 - 36}$$

$$B = \sqrt{160}$$

$$B = 12.65$$

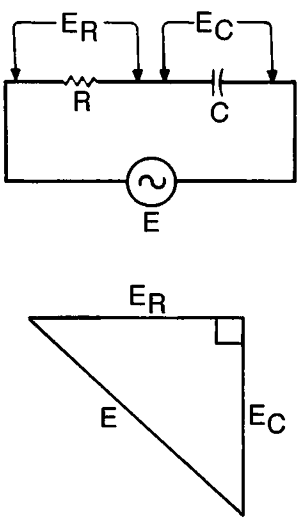


Figure A7

Right triangles are often used to solve electronic problems. They are particularly useful when you need to solve problems in circuits that contain inductance or capacitance. Inductors or capacitors introduce a 90° phase shift into the circuit. This 90° shift is represented by the right angle. The lengths of the sides of a right angle can represent the voltages in a simple series RC circuit.

In Figure A7, which voltage is represented by the hypotenuse? ________.

18. (E, applied voltage) Instead of using A, B and C for the sides, you use E_R, E_C and E.

Write the formula for finding the applied voltage if you know the resistor and capacitor voltages. ____________.

19. ($E = \sqrt{(E_R)^2 + (E_C)^2}$) The formula for the applied voltage is the same as the formula for finding the hypotenuse. You can also use the length of the side of a right triangle to show the relationship between the resistance, capacitive reactance, and the impedance of a series RC circuit. In this circuit, the lengths of the sides are expressed in ____________.

20. (ohms) Remember that the unit of measurement for resistance, reactance, and impedance is ohms.

Figure A8 shows a right triangle that relates these quantities.

Write the formula for computing the impedance. ___________ .

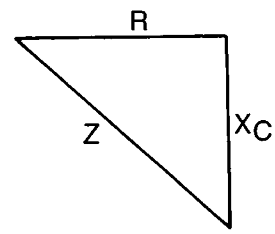


Figure A8

21. ($Z = \sqrt{R^2 + X_C^2}$) In this expression, the hypotenuse of the right triangle is ___________ .

22. (Z or impedance) If the resistance is 40 ohms and the capacitive reactance is 60 ohms, the impedance is ____________ ohms.

23. (72.1) The solution is as shown below:

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{(40)^2 + (60)^2}$$

$$Z = \sqrt{1600 + 3600}$$

$$Z = \sqrt{5200}$$

$$Z = 71.2 \text{ ohms}$$

What is the formula for finding the reactance if you know the resistance and impedance? X_C = ___________ .

24. ($X_C = \sqrt{Z^2 - R^2}$) You know the impedance Z (the hypotenuse) and the resistance R (one side). To find the reactance X_C (the other side) you use the formula.

As you can see, you can adapt the basic right triangle formula to any application that involves the electrical quantities in an RC circuit. Just remember that the formulas apply only to right triangles.

APPENDIX B: INTRODUCTION TO TRIGONOMETRY

The purpose of this lesson is to give you the basic concepts and skills that will permit you to use trigonometry in the solution of electronic circuit problems.

Read each of the numbered frames below in sequence. Answer the question in each frame by filling in the blank before you go on to the next frame. Keep the frames below the one you are reading covered with a piece of paper to avoid the temptation to look at the answer. Start now with frame 1.

NOTE: If you have not read Appendix A, please do so before you begin this lesson.

1. Trigonometry (often shortened to trig) is the study of triangles. It provides a system of dealing with triangles on a mathematical basis. More specifically, trigonometry gives you methods and procedures to help you calculate the lengths of the sides and the angles of a triangle. The sizes of the angles and the sides are related in a very unique way. The study of triangles is called ___________.

2. (trigonometry) While trig provides techniques to help you solve any type of triangle, the discussion here is limited to trig as it applies to right triangles.

   A right triangle is a three-sided geometric figure that has one ___________ angle.

3. (right) A right angle, as you recall, has ___________ degrees.

4. (90) With trigonometry, you can quickly calculate the sides and angles of a right triangle. If you know the length of one side and the size of one angle (other than the right angle), you can readily determine the sizes of all other sides and angles.

There are six basic trigonometry functions. These are ratios that express the relationship between one of the two acute angles in a right triangle and two of the sides. The size of the angle is a direct function of the lengths of the related sides.

In the same way, the lengths of any two sides are a direct function of the size of the related ___________.

5. (angle) Refer to Figure A9. You will use this right triangle to show the basic trig functions. Note that one of the acute angles has been selected for use in expressing the functions. We call this angle θ (the Greek letter theta), and the sides are labeled with reference to this angle. The side directly across from θ is called the opposite side (O). The side next to θ is called the adjacent side (A).

Of course, the side opposite the right angle is always called the ___________.

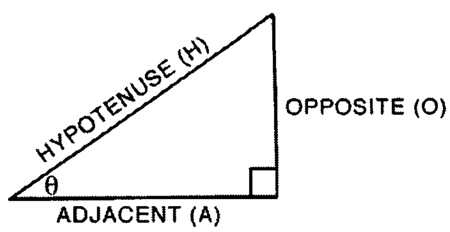


Figure A9

6. (hypotenuse) The six basic trig functions of the angle θ in Figure A9 are:

$$\text{sine } \theta = \frac{\text{opposite}}{\text{hypotenuse}} \qquad \text{sine } \theta = \frac{O}{H}$$

$$\text{cosine } \theta = \frac{\text{adjacent}}{\text{hypotenuse}} \qquad \cos \theta = \frac{A}{H}$$

$$\text{tangent } \theta = \frac{\text{opposite}}{\text{adjacent}} \qquad \cos \theta = \frac{O}{A}$$

$$\text{secant } \theta = \frac{\text{hypotenuse}}{\text{opposite}} \qquad \sec \theta = \frac{H}{O}$$

$$\text{cosecant } \theta = \frac{\text{hypotenuse}}{\text{adjacent}} \qquad \csc \theta = \frac{H}{A}$$

$$\text{cotangent } \theta = \frac{\text{adjacent}}{\text{opposite}} \qquad \cot \theta = \frac{A}{O}$$

Of these six, only the first three are widely used. You will learn about only these three functions in this lesson.

Consider the sine function above. This expression tells you that the numerical value of sine θ is the ratio of the ___________ side and the ___________.

7. (opposite, hypotenuse) The ratio of the length of the opposite side to the length of the hypotenuse is the numerical value that indicates the size of θ. For example, if the opposite is 3 and the hypotenuse is 6, then:

$$\sin \theta = \frac{3}{6} = .5$$

A value of .5 corresponds to an angle of 30° or:

$$\sin 30° = .5$$

Regardless of the actual lengths of the sides of the triangle, if the ratio of the opposite to hypotenuse is .5, the angle is 30°.

If H = 20 and O = 10, the sine is ___________.

8. (.5) $\text{sine } \theta = \frac{O}{H} = \frac{10}{20} = .5$

Mathematicians have computed all of the ratios of the various sides and determined the corresponding angles. All of this information has been put into a table for convenient reference. See Appendix C. If you want to find the sine of 30° you just find 30° in the Degrees column. Then you locate the number to the right of 30° in the Sine column.

What is the sine of 42°? (Use Appendix C.) Sine 42° = __________.

9. (.669) This means that the ratio of the opposite side to the hypotenuse is .669.

$$\sin 42° = \frac{O}{H} = .669$$

You can also use the tables in Appendix C to find the cosine or tangent of an angle. To do this, you first locate the angle in the Degrees column. Then you locate the desired numerical ratio in either the Cosine or Tangent columns.

The cosine of 30° is __________.

10. (.866) What is the tangent of 9°? Tan 9° = __________.

11. (.158) Trig tables are easy to use. First find the angle in the Degrees column. Then find the sine, cosine, or tangent of that angle to the right in the appropriate column.

The tangent is the ratio of the __________ to __________ side.

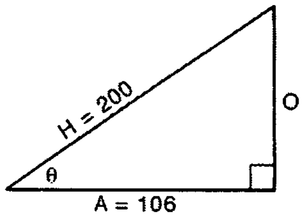


Figure A10

12. (opposite, adjacent) $\tan\theta = \frac{O}{A}$

The angle θ is the angle whose cosine is the ratio of the adjacent side to the hypotenuse.

Refer to Figure A10. The cosine of θ is ___________.

13. (.53) The cosine is the ratio of the adjacent to the hypotenuse or:

$$\cos\theta = \frac{A}{H} = \frac{106}{200} = .53$$

The angle corresponding to a Cosine of .53 (from Appendix C) is ___________.

14. (58°) If O = 77 and A = 77, $\tan\theta$ = ___________.

15. (1) $\tan\theta = \frac{O}{A} = \frac{77}{77} = 1$

What angle does this correspond to? θ = ___________.

16. (45°) In Appendix C you look up 1 in the Tangent column. Then you locate the corresponding angle in the Degrees column.

When the opposite and adjacent sides are equal, the tangent is always 1 and this corresponds to an angle of 45°.

In a right triangle, angle θ = 45°. The adjacent side is 14. The opposite side is ___________.

17. (14) When you use basic algebra to rearrange the basic trig formulas, you can compute the length of any side if you know the angle and one other side. This is illustrated below with the sine:

$$\sin \theta = \frac{O}{H}$$

$$O = H \sin \theta$$

$$H = \frac{O}{\sin \theta}$$

For example, if the hypotenuse is 150 and $\theta = 30°$, the opposite side is:

$$O = H \sin \theta = 150 \sin 30°$$

$$O = 150\,(.5) = 75$$

If $H = 90$ and $\theta = 60°$, $O =$ ___________.

18. (78) $O = H \text{ sine } \theta = 90 \sin 60° = 90\,(.886) = 77.94$ or approximately 78. To solve this problem, you look up the sine of 60° in the tables, and then multiply it by the length of the hypotenuse.

Since you know the opposite side and the angle, you can compute the hypotenuse:

$$H = \frac{O}{\sin \theta}$$

The opposite side is 15 and the angle is 55°. The hypotenuse is ___________.

19. (18.3) You look up the sine of 55° in the table then divide it into the length of the opposite side.

$$H = \frac{O}{\sin\theta} = \frac{15}{\sin 55^\circ} = \frac{15}{.819} = 18.3$$

You can also rearrange the cosine function to solve for any side.

$$\cos\theta = \frac{A}{H}$$

$$A = H\cos\theta$$

$$H = \frac{A}{\cos\theta}$$

If you know the angle and the length of the hypotenuse, which formula would you use to compute the adjacent side? __________.

20. ($A = H\cos\theta$) If $H = 70$ and $\theta = 20^\circ$, $A =$ __________.

21. (65.8) $A = H\cos\theta = 70\cos 20^\circ = 70\,(.94) = 65.8$. Since you know the adjacent side and the angle, you can find the hypotenuse.

$$H = \frac{A}{\cos\theta}$$

If $A = 24$ and $\theta = 68^\circ$, $H =$ __________.

22. (66.7) $H = \frac{A}{\cos\theta} = \frac{25}{\cos 68^\circ} = \frac{25}{.375} = 66.7$

Here are the formulas you use to compute the opposite and adjacent sides if you know the tangent of the angle:

If you know the opposite side and angle, which formula would you use to compute the length of the adjacent side? __________.

23. ($A = \frac{O}{\tan\theta}$) If $O = 17$ and $\theta = 36^\circ$ $A =$ __________.

24. (23.4) $A = \frac{O}{\tan\theta} = \frac{17}{\tan\ 36°} = \frac{17}{.727} = 23.4$

To compute the opposite side you use the expression $O = A \tan\theta$ if you know the __________ side and __________.

25. (adjacent, angle) $O = A \tan\theta$. If $A = 40$ and $\theta = 45°$, $O =$ __________.

26. (40) If $\theta = 45°$, $A = O$. What is the opposite side if the adjacent side is 115 and $\theta = 80°$? $O =$ __________.

27. (652) $O = A \tan\theta = 115 \tan 80° = 115\ (5.671) = 652$.

Right triangles are widely used in electronics to solve circuit problems. The lengths of the sides of the triangle represent voltages, currents, or impedances. The angle represents the circuit phase shift.

Refer to Figure A11. This triangle represents an RC circuit. The sides of the triangle represent circuit __________.

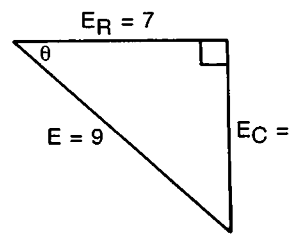


Figure A11

28. (voltages) The hypotenuse represents the applied voltage E. The adjacent side represents the voltage across the resistor E_R. The voltage across the capacitor is represented by the __________ side.

29. (opposite) The phase angle of the circuit represented by the triangle in Figure A11 is __________.

30. (39°) The adjacent side and the hypotenuse are given in Figure A11. Therefore you use the cos.

$$\cos\theta = \frac{A}{H} = \frac{7}{9}$$

$$\cos\theta = .777$$

$$\theta = 39°$$

Compute the capacitor voltage in Figure A11.
$E_C =$ __________ volts.

31. (5.66) You could use the sine function since you want to compute the opposite side. The adjacent side and hypotenuse are given in Figure A11 and H was computed in the previous frame.

$$O = H \sin \theta$$

$$O = 9 \sin 39°$$

$$O = 9(.629) = 5.66 \text{ volts}$$

What other trig function could you use to compute the opposite side? ________.

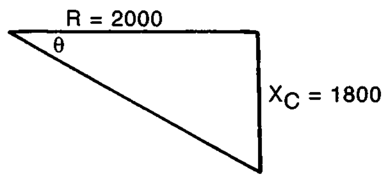


Figure A12

32. (tangent) $\tan \theta = \frac{O}{A}$

You know the angle and the adjacent side, therefore:

$$O = A \tan \theta$$

$$O = 7 \tan 39°$$

$$O = 7(.81) = 5.67 \text{ volts}$$

Refer to Figure A12. The hypotenuse represents what quantity? ________.

33. (impedance or Z) What is the phase angle of the circuit represented by this triangle? $\theta =$ ________.

34. (42°) $\tan \theta = \frac{O}{A} = \frac{1800}{2000} = .9$

You know the opposite side (capacitive reactance) and the adjacent side (resistance). Their ratio is the tangent, and the corresponding angle, from Appendix C, is 42°. The impedance of this circuit is ________ ohms.

35. (2691) Since you know the phase angle and both the opposite and adjacent sides, you can use either sine or cosine.

$$H = \frac{O}{\sin\theta} = \frac{X_C}{\sin\theta} = \frac{1800}{\sin 42°} = \frac{1800}{.669} = 2691 \text{ ohms}$$

$$H = \frac{A}{\cos\theta} = \frac{R}{\sin\theta} = \frac{2000}{\cos 42°} = \frac{2000}{.743} = 2691 \text{ ohms}$$

As you can see, to solve AC circuit problems with trig, you first identify all of the data you have available. Then you determine the quantities to be computed. Finally, you select the appropriate trig function and compute your answer.

APPENDIX C: TABLE OF TRIGONOMETRIC FUNCTIONS

Degrees	Sine	Cosine	Tangent	Degrees	Sine	Cosine	Tangent
0	0.000	1.000	0.000				
1	0.017	1.000	0.017	46	0.719	0.695	1.036
2	0.035	0.999	0.035	47	0.731	0.682	1.072
3	0.052	0.999	0.052	48	0.743	0.669	1.111
4	0.070	0.998	0.070	49	0.755	0.656	1.150
5	0.087	0.996	0.087	50	0.766	0.643	1.192
6	0.105	0.995	0.105	51	0.777	0.629	1.235
7	0.122	0.993	0.123	52	0.788	0.616	1.280
8	0.139	0.990	0.141	53	0.799	0.602	1.327
9	0.156	0.988	0.158	54	0.809	0.588	1.376
10	0.174	0.985	0.176	55	0.819	0.574	1.428
11	0.191	0.982	0.194	56	0.829	0.559	1.483
12	0.208	0.978	0.213	57	0.839	0.545	1.540
13	0.225	0.974	0.231	58	0.848	0.530	1.600
14	0.242	0.970	0.249	59	0.857	0.515	1.664
15	0.259	0.966	0.268	60	0.866	0.500	1.732
16	0.276	0.961	0.287	61	0.875	0.485	1.804
17	0.292	0.956	0.306	62	0.883	0.469	1.881
18	0.309	0.951	0.325	63	0.891	0.454	1.963
19	0.326	0.946	0.344	64	0.899	0.438	2.050
20	0.342	0.940	0.364	65	0.906	0.423	2.145
21	0.358	0.934	0.384	66	0.914	0.407	2.246
22	0.375	0.927	0.404	67	0.921	0.391	2.356
23	0.391	0.921	0.424	68	0.927	0.375	2.475
24	0.407	0.914	0.445	69	0.934	0.358	2.605
25	0.423	0.906	0.466	70	0.940	0.342	2.748
26	0.438	0.899	0.488	71	0.946	0.326	2.904
27	0.454	0.891	0.510	72	0.951	0.309	3.078
28	0.469	0.883	0.532	73	0.956	0.292	3.271
29	0.485	0.875	0.554	74	0.961	0.276	3.487
30	0.500	0.866	0.577	75	0.966	0.259	3.732
31	0.515	0.857	0.601	76	0.970	0.242	4.011
32	0.530	0.848	0.625	77	0.974	0.225	4.332
33	0.545	0.839	0.649	78	0.978	0.208	4.705
34	0.559	0.829	0.675	79	0.982	0.191	5.145
35	0.574	0.819	0.700	80	0.985	0.174	5.671
36	0.588	0.809	0.727	81	0.988	0.156	6.314
37	0.602	0.799	0.754	82	0.990	0.139	7.115
38	0.616	0.788	0.781	83	0.993	0.122	8.144
39	0.629	0.777	0.810	84	0.995	0.105	9.514
40	0.643	0.766	0.839	85	0.996	0.087	11.43
41	0.656	0.755	0.869	86	0.998	0.070	14.30
42	0.669	0.743	0.900	87	0.999	0.052	19.08
43	0.682	0.731	0.933	88	0.999	0.035	28.61
44	0.695	0.719	0.966	89	1.000	0.017	57.29
45	0.707	0.707	1.000	90	1.000	0.000	

UNIT 4

INDUCTIVE CIRCUITS

CONTENTS

INTRODUCTION

In this unit you will study inductors and how they are used in AC circuits. An inductor is an electronic component that opposes changes in the current flow through it. Like a capacitor, it offers opposition to the flow of alternating current. When an inductor is used in sinusoidal circuits, it introduces a phase shift. You can combine inductors with resistors and/or capacitors to form a variety of electronic circuits.

Your previous studies in DC electronics should have included inductors and inductive circuits. You should know what an inductor is, how it works, and what effect it has in DC circuits. The first part of this unit is devoted to a review of inductors and inductance.

In the remaining sections, you will study the effects of inductance in an AC circuit. You will also consider the characteristics and applications of simple resistor-inductor, RL, networks.

Inductance is a characteristic that is present in virtually all electronic circuits. You must understand its effect in order to analyze, design, or troubleshoot electronic circuits. In addition, your understanding of inductance is vital to your successful completion of the units that deal with transformers and tuned circuits.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define inductance, inductive reactance, self inductance, mutual inductance, coefficient of coupling, and RL filter.

2. Draw a vector diagram which illustrates the phase relationship between voltage and current in an RL circuit.

3. Determine the impedance of an RL circuit.

4. Calculate the phase angle for a series or a parallel RL circuit.

5. Determine the inductive reactance of an inductor when you are given the inductance and frequency.

6. Determine the inductance of an inductor when you are given the inductive reactance and frequency.

7. Determine the Q of an inductor.

8. Name three applications for RL circuits.

9. Name four factors that affect the inductance of a coil.

10. Explain the relationship of the L/R time constant.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "Review of Inductors and Inductance."	________
☐ Complete Programmed Review Frames 1-39.	________
☐ Read "Inductors in AC Circuits."	________
☐ Complete Programmed Review Frames 40-77.	________
☐ Read "RL Circuits."	________
☐ Complete Programmed Review Frames 78-102.	________
☐ Perform Experiment 6: RL Circuits.	________
☐ Read "Applications of Inductive Circuits."	________
☐ Complete Programmed Review Frames 103-124.	________
☐ Complete the Unit Examination.	________
☐ Check the Examination Answers.	________

REVIEW OF INDUCTORS AND INDUCTANCE

When current flows through an electrical conductor such as a wire, it generates a magnetic field around the wire. Each electron in the conductor has a minute magnetic field that is associated with it. The electrons in the conductor are aligned in a random manner, when no current is flows through it. For that reason, the tiny magnetic fields that are associated with each electron tend to cancel one another. With no current flows through the conductor, no external magnetic field exists. When a voltage is applied to the conductor, electrons begin to flow. This tends to align the electrons so that their magnetic fields add. The total strength of the magnetic field is the sum of the individual electron fields. The higher the applied voltage or the lower the resistance of the conductor, the greater the number of electrons that will flow. The magnitude of the magnetic field that surrounds the conductor increases as the amount of current flow increases. This effect is known as electromagnetism. See Figure 4-1.

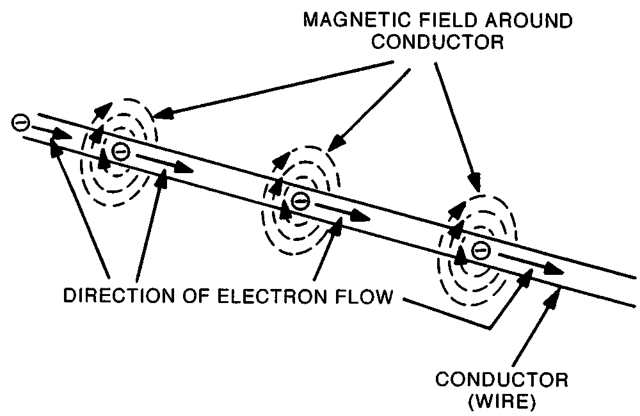


Figure 4-1
Magnetism around a current-carrying conductor.

Current that flows in a conductor produces a magnetic field. In addition, a magnetic field can cause a current to flow in a conductor. This current flows when there is relative motion between the magnetic field and the conductor. When a conductor or wire passes through a stationary magnetic field, a voltage or electromotive force (emf) is induced into that conductor. Alternately, when a magnetic field asses across a fixed conductor, a voltage is induced into the conductor. As long as there is relative motion between the magnetic field and the conductor, an induced voltage is generated in the conductor. As the conductor moves, the magnetic fields of the electrons in the conductor are affected by the external magnetic field. The motion between the conductor and the magnetic field forces the electrons to move in one direction or the other. This effect creates a small voltage across the conductor. There is a difference of potential from one end of the conductor to its opposite end. If the conductor forms a complete electrical circuit, current will flow in the circuit. See Figure 4-2.

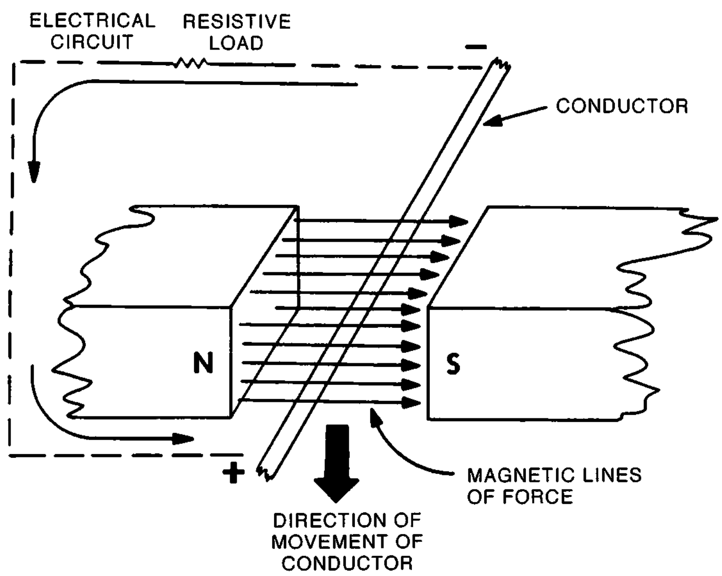


Figure 4-2
Electromagnetic induction.

The amount of voltage that is induced into a conductor by its motion in a magnetic field depends upon the strength of the magnetic field. The stronger the field, the more influence it has on the electrons inside the conductor, and the greater the induced voltage. The length of the conductor also determines the amount of induced voltage. For a given magnetic field, the longer the conductor, the greater the induced voltage. The speed with which the conductor cuts the magnetic field also influences the magnitude of the induced voltage. When the conductor moves through the field slowly, it causes only a small voltage to be induced. When the conductor moves quickly through the magnetic field, a larger voltage is induced.

The direction of motion between the conductor and the magnetic field also determines the amount of induced voltage. When the conductor moves in the same direction and at the same speed as the magnetic field, no voltage is induced. The conductor must cut across the magnetic lines of force in order for a voltage to be generated. When the conductor moves perpendicular (90 degrees) to the magnetic lines of force, maximum voltage is induced. As you can see, the amount of induced voltage is directly proportional to the strength of the magnetic field, the length of the conductor, the speed of the conductor, and the direction of movement of the conductor relative to the magnetic field. This effect is known as electromagnetic induction. Electromagnetism and electromagnetic induction are both responsible for the property of inductance and the effect it has on electrical circuits.

Self-Induction

When voltage is applied to a conductor, current will flow. This current flow generates a magnetic field around the conductor. This field, however, is not created immediately when voltage is applied to the conductor. Rather, the field builds gradually as current flow through the conductor increases. When current flow reaches its maximum value, the magnetic field around the conductor is at its maximum strength.

As the magnetic lines of force expand outward from the center of the conductor, the magnetic field causes a voltage to be induced into the conductor itself. In other words, the magnetic field generated by the conductor causes a voltage to be induced into the conductor which produces the magnetic field. The expansion of the magnetic lines of force with respect to the conductor represents the relative motion between the conductor and the magnetic field that is required to induce a voltage. The polarity of the induced voltage opposes the polarity of the voltage that causes it.

As long as the magnetic field moves with respect to the conductor, an induced voltage is generated. As the magnetic lines of force continue to expand outward from the conductor during the rise of the current in the circuit, induced voltage is present. When the current in the circuit reaches its maximum, as determined by the applied voltage and the resistance of the conductor, the magnetic field becomes stationary. Since there is no further relative motion between the conductor and the magnetic field, there is no induced voltage. At this time, the current in the circuit is strictly a function of Ohm's Law.

When you remove the voltage that is applied to the conductor, current flow decreases. With less movement of electrons in the conductor, the magnetic field starts to collapse. As it collapses, the lines of force cut across the conductor and induce a voltage. Again, the collapsing lines of force cause relative motion between the conductor and the magnetic field. Therefore, a voltage is induced into the conductor. The polarity of the induced voltage is such that it tends to keep the current flowing in the same direction as dictated by the external applied voltage.

Application or removal of the voltage source causes a self-induced voltage. This self induction takes place for any current changes that occur. When the current increases or decreases in a circuit, it causes the magnetic lines of force to expand or collapse and thereby cut the conductor, which induces a voltage that opposes the applied voltage. The induced voltage is referred to as counter emf or back emf since it always opposes the applied voltage. The ability of a conductor to generate a voltage with a change in current is called self-induction. It is this characteristic that produces the property called inductance.

Inductors and Inductance

Inductance is the property of an electrical circuit that tends to oppose any change of current in the circuit. The conductor or wire in the circuit exhibits the property of inductance because it opposes changes in the current flow. When the current through a conductor suddenly increases, a voltage is induced within the conductor that opposes the applied voltage. The induced voltage attempts to cancel the applied voltage and tends to hold the current to its previous level. The induced voltage opposes the applied voltage, which opposes the increase in current. The current still rises, however, because the induced voltage appears only during the time that the current increases, the rate of increase is slows. Once there is no longer a relative motion between the conductor and the magnetic field, no further induced voltage or additional opposition takes place.

When the current in a circuit suddenly decreases, the magnetic lines of force collapse and induce a voltage into the conductor that opposes the applied voltage. When the applied voltage suddenly decreases, the induced voltage maintains the current at the same level. The current eventually decreases, however, as the magnetic field stops collapsing and no further induced voltage is generated.

As you can see, when the current in a circuit changes, it causes a voltage to be induced into the conductor that opposes the change of current. The induced voltage tends to cause current in the circuit to remain constant, at least this is true for a short period of time. This ability to oppose the change in an electrical current is defined as inductance.

The electronic component that most exhibits the property of inductance is called an inductor. The conductor or wire that you have been considering up to this point is referred to as an inductor. While any wire or electrical conductor exhibits the property of inductance, it is normally not referred to as an inductor. Instead, an inductor is considered to be a separate and distinct type of passive electronic component. The most common inductor is a coil of wire. The term coil is often used interchangeably with the name inductor.

Whenever a wire is wound into a coil, the coil forms an inductor which becomes more manageable. When the wire is wound into a coil, it makes the inductor smaller and more compact. At the same time, inductance greatly increases. When you keep the turns of wire close together, the magnetic field surrounding the wire becomes more concentrated. The greater the magnetic field, the greater the induced voltage and therefore the higher its inductance.

Unit of Inductance

The unit of electrical inductance is the henry. One henry is defined as the amount of inductance that a coil has when the current, changing at the rate of one ampere per second, produces one volt of induced voltage. Inductance is a measure of how much counter emf is generated in an inductor for a specific amount of change in the current through that inductor.

The henry, abbreviated H, is a fairly large unit of inductance. While there are inductors available with an inductance of one henry or more, most inductors in electronic circuits have a much lower inductance value. These inductance values are expressed in smaller units known as the millihenry (mH) and microhenry (μH). One millihenry is one thousandth of a henry. One microhenry is one millionth of a henry. One microhenry is also one thousandth of a millihenry. In formulas, inductance is usually indicated by the letter L.

Table I shows the relationship between the henry, the millihenry, and the microhenry. Table II shows you how to convert from one unit of inductance to another.

TABLE I

Units of Inductance.

1 henry	= 1000 or 10^3 millihenry
1 henry	= 1,000,000 or 10^6 microhenry
1 millihenry	= 1/1000 or 10^{-3} henry
1 millihenry	= 1000 or 10^3 microhenry
1 microhenry	= 1/1000000 or 10^{-6} henry
1 microhenry	= 1/1000 or 10^{-3} millihenry

Henry = H
Millihenry = mH
Microhenry = μH

TABLE II

How to convert units of inductance.

To Convert	To	Action
Henry	Millihenry	Multiply by 1000 (10^3) or move the decimal point three places to the right.
Henry	Microhenry	Multiply by 1,000,000 (10^6) or move the decimal point six places to the right.
Millihenry	Henry	Divide by 1000 (10^3) or move the decimal point three places to the left.
Millihenry	Microhenry	Multiply by 1000 (10^3) or move the decimal point three places to the right.
Microhenry	Henry	Divide by 1,000,000 (10^6) or move the decimal point six places to the left.
Microhenry	Millihenry	Divide by 1000 (10^3) or move the decimal point three places to the left.

The following examples also show you how to use the information in Tables I and II to convert from one unit to another.

1. Convert 100 mH to H. 100 mH = 100 / 1,000 = .1 H.

2. Convert 78.6 μH to H. 78.6 μH = 78.6 / 1,000,000 = .0000786 H or 78.6×10^{-6} H.

3. Convert 22 mH to μH. 22 mH = $22 \times 1,000$ = 22,000 μH.

Factors That Affect Inductance

The physical characteristics of a coil determine its inductance. The amount of inductance that a coil has depends upon the number of turns in the coil, the spacing between the turns, the wire size, the shape of the coil, the number of layers of windings, the type of windings, the diameter of the coil, the length of the coil, and the type of core material. Refer to Figure 4-3.

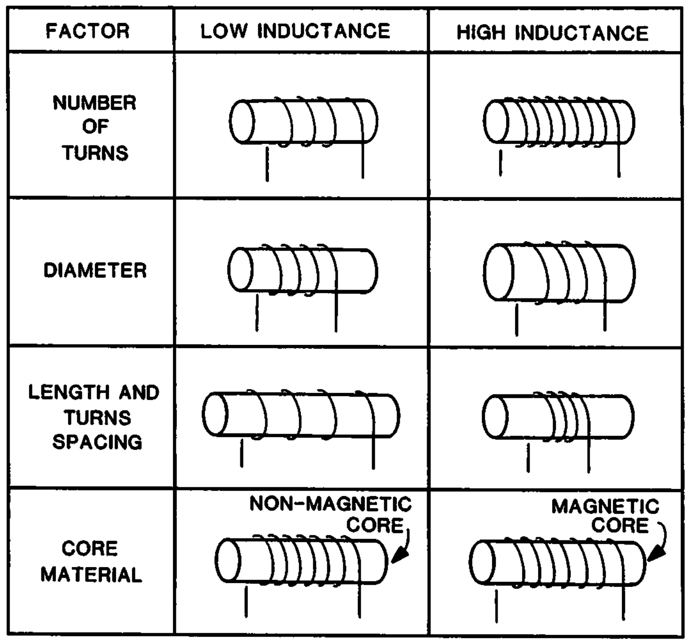


Figure 4-3
Factors that influence inductance.

The inductance of a coil is directly proportional to the number of turns of wire and the diameter of the coil. The greater the number of turns, the greater the magnetic field that is produced by the coil. And for a given number of turns, the greater the diameter of the coil, the more magnetic lines of force are produced. Anything you do to increase the magnetic field that is produced by the coil will increase its inductance.

The spacing between the turns also affects the inductance. When you keep the turns very close together, the magnetic lines of force that are produced by each turn add together and produce a stronger magnetic field. More space between the

turns of the coil reduces the addition of the lines of force that are produced by each turn. This additive effect is called mutual inductance, and you can adjust the spacing between the turns to increase or decrease it. The spacing of the turns also affects the coil's length. Inductance is inversely proportional to the length of the coil. That is, when you increase the length, you decrease the inductance. When you increase the length, the resistance also increases, which reduces current flow. Current flow is the movement that results in the property called inductance. The length of the wire you use to make the coil is not the same as the length of the conductor in a magnetic field.

The size of the wire in the coil does not directly affect the inductance of the coil, but it does influence the spacing between the turns when the turns are directly adjacent to one another. The smaller the wire, the closer the turns and the greater the inductance. The diameter of the conductor wire that forms the coil is a factor, but a smaller diameter allows a greater number of turns to be formed, which is a much more important factor.

The number of layers of winding also affect the inductance. The greater the number of windings, the greater the inductance. The shape of the coil and the method of winding the wire also affects the inductance. Keep in mind that the closer the turns and the greater the alignment of the various layers of wire, the greater the magnetic field that can be produced for a given amount of current and, therefore, the greater the inductance.

The type of core material in the coil also affects the inductance. Core material refers to the type of form on which the wire is wound. Many coils are self-supporting and have no form or core. Such coils are referred to as air-core inductors. The inductance of an air-core coil is strictly a function of the factors you just learned. A core, however, affects the inductance.

Most inductors are made with a core that has magnetic properties. Cores that are made of iron, steel, nickel, or some related alloy can support a magnetic field. Such cores concentrate the magnetic lines of force that are produced by the coil, which increases the intensity of the magnetic field. This increases the amount of induced voltage and, therefore, the inductance.

It is the permeability of the core material that determines its effect on the inductance of the coil. Permeability is the ability of a material to support the magnetic lines of force. The greater the ease with which magnetic lines of force can be set up within the core materials, the higher the permeability. Air has a permeability of 1 while a magnetic material like iron has a permeability of 7000.

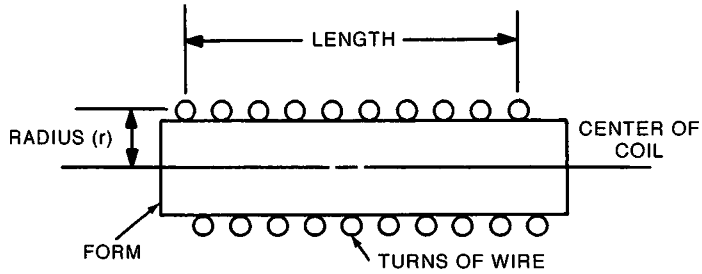


Figure 4-4
Cross-section view of
a singe layer inductor.

The following formula relates all of these factors in a formula that you can use to compute the inductance of a single-layer inductor. This is shown in Figure 4-4.

$$L = \frac{.04\mu\, N^2\, r^2}{l}$$

L is the inductance in microhenrys, N is the number of turns, r is the radius of the coil in centimeters (1 inch = 2.54 centimeters), l is the coil length in centimeters and μ is the permeability. For example, an air-core coil with a radius of 2 CM, a length of 7 CM, and 100 turns has an inductance of:

$$L = \frac{.04(1)\,(100)^2\,(2)^2}{7} = \frac{1600}{7} = 228.57\ \mu H$$

NOTE: An air core has a permeability (μ) of 1.

Types of Inductors

There are two basic types of inductors that are used in electronic circuits, fixed inductors and variable inductors. Fixed inductors are further classified by their type of core material. The two major kinds of fixed inductors are air-core and iron-core. Variable inductors are inductors whose inductance value can be varied. Most variable inductors use an iron-core.

FIXED INDUCTORS

Basically all inductors are made by winding a length of wire around a core. Solid copper wire with an enamel insulation is the most commonly used conductor. The core can be a non-conducting non-magnetic material such as bakelite, plastic, or ceramic. The primary purpose of these cores is to support the coil of wire.

These cores have no magnetic properties and, therefore, do not affect the inductance of the coil. When a coil is made of heavy wire, a form may not be needed for support. The wire may be rigid enough to support itself. Coils with non-magnetic forms or no form at all are referred to as air-core inductors. Their coils generally have very low values of inductance. Air cores are usually used in high frequency applications. Figure 4-5A is the schematic symbol of an air-core inductor.

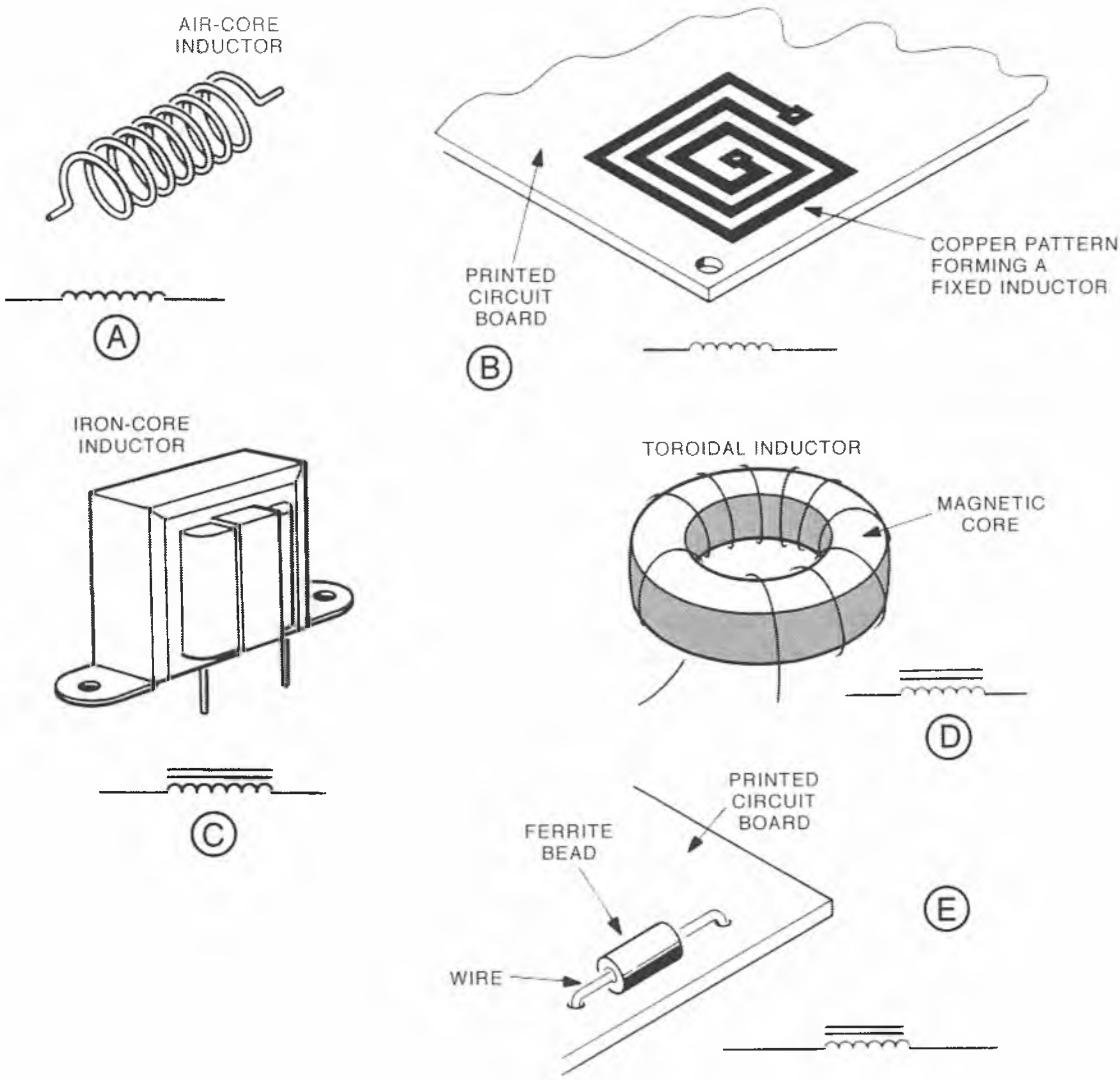


Figure 4-5
Typical fixed inductors. (A) air-core, (B) printed circuit inductor, (C) iron-core choke, (D) toroidal inductor, and (E) ferrite bead inductor and their schematic symbols.

Figure 4-5B shows a special type of fixed inductor. The inductor is a spiral of copper foil on a printed circuit board. The advantage of such a coil is that it can be formed during manufacture of the printed circuit board. The physical configuration that is dictated by this type of construction allows you to obtain only very small values of inductance. This type of inductor is widely used in high-frequency circuits.

Another common type of fixed inductor is the iron-core choke. The term choke is used interchangeably with inductor. In this type of inductor, a multi-layered coil is wound on a laminated iron-core. The iron-core has magnetic properties that concentrate the magnetic field, which increases its inductance. Values of inductance that approach 100 henrys are possible with such iron-core chokes. Iron-core inductors such as this are used primarily in DC and low-frequency AC applications. Figure 4-5C shows a typical iron-core choke and its schematic symbol.

Another specially-shaped iron-core choke is the toroidal inductor shown in Figure 4-5D. The donut-shaped core is either a powdered iron called ferrite or a spiral wound tape of magnetic metal. Toroids are used in both low- and high-frequency applications. At one time, toroidal coils were used extensively in digital computer memories. Some older computers may still use core memories, but solid-state integrated circuit memory is much more common today.

A special iron-core fixed inductor is the ferrite bead inductor shown in Figure 4-5E. Here, a tiny cylindrical-shaped ferrite bead is simply slipped around a wire conductor. The short wire has inductance, but the ferrite bead concentrates and intensifies the magnetic field around the wire. The small ferrite bead increases inductance without adding critical spacing, size, or much additional weight to the circuit. You can obtain only small values of inductance with a bead, but such small inductors are very useful in high-frequency applications.

VARIABLE INDUCTORS

A variable inductor's inductance can be changed. Most variable inductors consist of a coil of wire that is wound on a non-magnetic form. The form contains a movable core. This core, which is usually made of powdered iron known as ferrite, is made adjustable. You can position of the core with respect to the coil so that the inductance value varies as the core moves into or out of the coil form. Variable inductors such as this are widely used in tuned circuits in radio applications. Figure 4-6 shows a typical variable inductor and its schematic symbol.

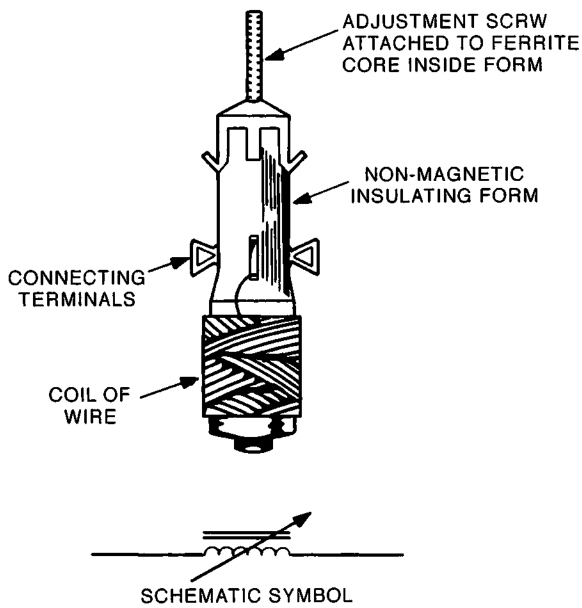


Figure 4-6
Typical variable inductor
and its schematic symbol.

Inductors in DC Circuits

Inductance has no effect upon direct current unless the DC changes (turns on, turns off, or pulsates). In most DC circuits, the current flow in the circuit is constant. When you use an inductor in a DC circuit, only the resistance of the wire affects the current. The property of inductance depends upon a changing current which produces a self-induced voltage. When the current in a DC circuit changes, the inductance affects it. The current in a DC circuit usually changes only when you apply or remove the voltage. An inductor in a DC circuit reduces AC ripple from the supply voltage and noise that might be riding on the DC.

Figure 4-7 shows inductor L connected to a DC source through a switch. When the switch is in position A, the inductor is not connected to the DC supply. When you move the switch to position B, the battery connects to the inductor. When you move the switch from position A to position B, the DC source voltage causes current to flow. The instant electrons begin to flow, a magnetic field is generated. As the magnetic field expands outward, it cuts the turns of the inductor and induces a counter emf. The polarity of the induced voltage opposes the applied voltage, and the amount of current flow in the circuit is initially limited. The opposition of the induced voltage does not allow the current in the circuit to rise instantaneously. Instead, it takes a finite period of time for the current to reach its maximum value.

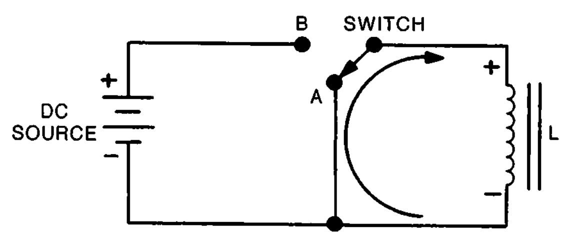


Figure 4-7
Inductance in a DC circuit.

The graph in Figure 4-8A shows how the current varies with time when you first apply a DC voltage to the inductor. Once the magnetic field stops expanding, no further counter emf is induced. It is at this time that current in the circuit is maximum. The amplitude of the applied voltage and the resistance of the inductor determines the maximum current.

The resistance of the inductor is its DC resistance, not its inductive reactance. Inductive reactance is an AC resistance and is defined as X_L. To DC, the inductor's resistance is usually very low. The DC resistance varies from a few ohms to a few hundred ohms. The actual DC resistance is a function of the type of conductor material used, its diameter, and its length. The AC resistance (inductive reac-

tance) is a function of the inductor's value in henries and the frequency of operation. Inductive reactance (X_L) will be described in the next section of this unit.

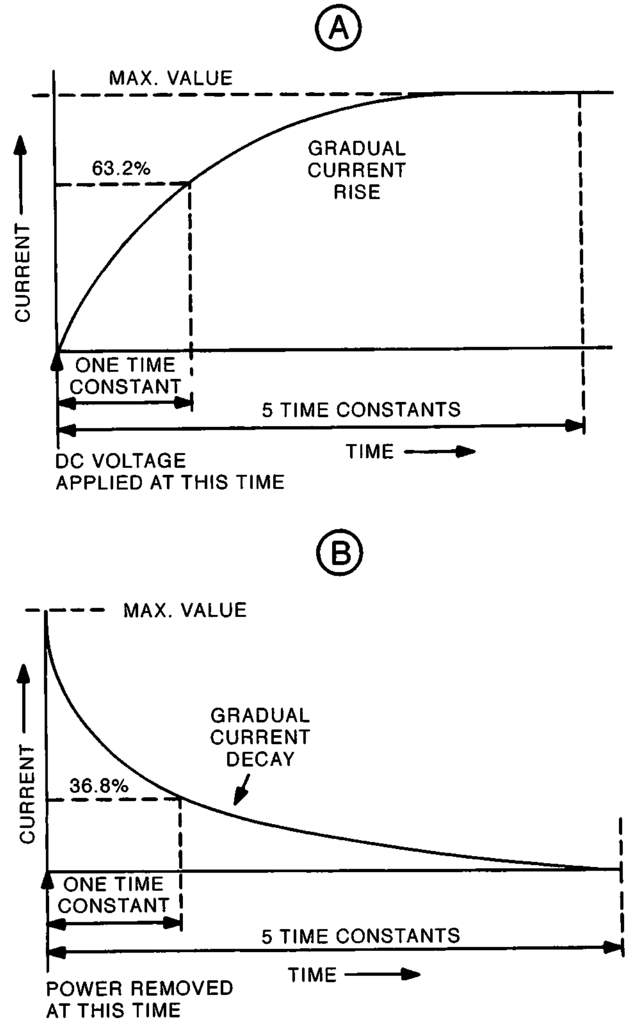


Figure 4-8
Variation of direct current in an inductor when (A) power is applied, and (B) power is removed.

When you move the switch from position B to position A, you break the connection to the DC source. This causes the magnetic field around the inductor to collapse. As it collapses, it induces a voltage when the magnetic field cuts the turns of the coil. When you remove the DC source voltage, current does not drop to zero instantaneously. Instead, the collapsing magnetic field induces a voltage which causes the current flow to continue in the same direction. When the magnetic field completely collapses, no further voltage is induced, and the current flow drops to zero. Figure 4-8B shows the decay in current when power is removed from the inductor.

As you can see from the graphs in Figure 4-8, the inductor clearly opposes changes in current in DC circuits. When you apply a voltage to the inductor, the inductor opposes (slows) the rise of current in the circuit. When you remove the voltage from the circuit, the inductor again keeps the current flowing in the same direction for a short time to opposes the change in current flow.

Inductive Time Constant

Whenever a DC voltage is applied to or removed from an inductor, it takes a definite period of time for the current to reach its maximum or minimum values. The effect is similar to the time that it takes for a capacitor to charge or discharge. The time that it takes the inductive circuit's current to rise or fall is referred to as the time constant of the inductor.

The time constant of an inductor is defined as the time required for the current to rise to 63.2% of its maximum value or to decrease to 36.8% of its maximum value. The time constant is illustrated in Figure 4-8.

The value of the inductive time constant is a function of the inductance and resistance in the circuit. The time constant is directly proportional to the inductance and inversely proportional to the resistance. The following equation expresses this relationship:

$$t = \frac{L}{R}$$

As you can see, the greater the inductance, the greater the time constant. Also, the greater the induced voltage, the greater the opposition to the applied voltage. This means that the current in the circuit takes longer to rise to its final or maximum value. The larger the resistance, the less the current and the lower the strength of the magnetic field and the induced voltage.

In this expression, t is in seconds, L is in henrys, and R is in ohms. For example, if a 1.5-henry choke has a resistance of 100 ohms, the time constant is:

$$t = \frac{1.5}{100} = .015 \text{ seconds or 15 milliseconds}$$

This means that it takes 15 milliseconds for the current to rise to 63.2% of its maximum value or to fall to a value of 36.8% of the maximum circuit current. It takes approximately 5 time constants for the current to rise to the maximum value from zero, or drop from its maximum value to zero. Note that the 5 time constants it takes the inductor to completely change between maximum and minimum is the same as a capacitor takes to completely charge and discharge.

Remember that in a capacitive circuit, current initially is maximum and the voltage reached its maximum across the capacitor after 5 time constants. In this case, current leads voltage. In a purely capacitive circuit, current leads voltage by 90°. In an inductive circuit, however, current initially is zero and voltage is maximum. In this case, voltage leads current. In a purely inductive circuit, voltage leads current by 90°. The voltage and current relationship becomes very important later in your studies when you combine capacitors and inductors in a variety of circuit configurations.

When the maximum current in the example above is 600 milliamperes, it takes 15 milliseconds for the current to rise to 63.2% of 600 or $.632 \times 600 = 379.2$ mA. It takes $5 \times 15 = 75$ milliseconds for the current to rise to the full 600 mA.

Programmed Review

1.	When current flows through a wire conductor, it generates a magnetic field. The magnitude of the field is proportional to the current. That is, to increase the strength of the magnetic field, you must __________ the current.
2.	(increase) The ability of a current flow to produce a magnetic field is called __________ .
3.	(electromagnetism) When there is relative motion between a conductor and a magnetic field, a voltage is induced into the conductor. This effect is referred to as __________ .
4.	(electromagnetic induction or induction) A voltage is induced only if the magnetic field or the conductor is __________ .
5.	(moving) The magnetic lines of force must cut across the inductor in order to induce a voltage. If the magnetic field changes (expands or collapses), the effect is the same as physical motion. To vary the magnetic field that is produced by a conductor, the __________ must vary.
6.	(current) When the current in a conductor varies, it causes the magnetic field that is generated to vary. If the magnetic field cuts across another conductor it __________ a voltage into the conductor.
7.	(induces) The changing magnetic field also cuts across the conductor which produces the magnetic field. As a result, the conductor that generates the varying magnetic field induces a voltage into itself. This process is called __________ __________ ,
8.	(self-induction) The polarity of the self-induced voltage is such that it opposes the applied voltage. This has the effect of __________ the circuit current.

9. (reducing or decreasing) The changes in current in the conductor produce a varying magnetic field that induces a voltage into the conductor. This self-induced voltage opposes the applied voltage and therefore the current. The property of an electrical circuit that opposes a change in current is called ___________.

10. (inductance) The electronic component that exhibits this characteristic is called a(n) ___________.

11. (inductor) Inductors are also called ___________ and ___________.

12. (coils, chokes) When inductors are manufactured, a wire conductor is wound into a coil on a form. A coiled wire concentrates the magnetic field. For a given length of wire and current, the magnetic field and therefore the self-induced voltage is higher with a coiled conductor. In other words, when you coil the wire, you increase the ___________.

13. (inductance) The unit of inductance is the ___________.

14. (henry) One henry is the inductance of a coil in which a current change of one ampere per second induces a voltage of one volt. Inductance is designated by the letter _________ and henry is abbreviated as _________.

15. (L, H) Smaller units of inductance are also commonly used. A common unit of inductance is the ___________ which represents one thousandth of a henry.

16. (millihenry) It takes 1000 millihenrys to make one henry. Millihenry is abbreviated _________.

17. (mH) Another even smaller unit of inductance is the microhenry. One microhenry is one ___________ of a henry and is abbreviated _________.

18. (millionth, µH) It takes one million µH to make one H. Or it takes one __________ µH to make one mH.

19. (thousand) It is often necessary to convert between these various units. To do this, you multiply or divide by the proper factor. For example, 123 mH = __________ H.

20. (.123) 123 mH ÷ 1000 = .123 H. Another example is 487 µH = __________ H.

21. (.000487) 487 µH. 1000000 = .000487 H. Convert .0035 H to mH and µH. .0035 H = __________ mH and __________ µH.

22. (3.5, 3500) A coil's physical characteristics determines the amount of inductance the coil has. List four of the important factors: __________, __________, __________, __________.

23. (number of turns, length, diameter, type of core) Anything you do to increase the intensity of the magnetic field produced by the coil will increase its inductance. For example, if you increase the number of turns, decrease the spacing between turns, and insert an iron core, the inductance will __________.

24. (increase) The two basic types of inductors are __________ and __________.

25. (fixed, variable) Fixed coils are further classified by the type of core material. The two kinds of cores most often used are __________ and __________.

26. (air, iron) A variable inductor usually uses an __________ core.

27. (iron) You move the core with respect to the coil of wire to vary the inductance. If you move the core out of the coil, it __________ its inductance.

28. (reduces or decreases) An inductor has no effect upon the operation of a DC circuit because the current is constant and does not vary. True or false? ____________ .

29. (true) However, when the DC is applied to or removed from the circuit, the current changes. Therefore the inductor attempts to ____________ the changes.

30. (oppose) It opposes the rise of current when you apply the DC voltage. It opposes the decrease of the current when you remove the DC voltage. Of course, the changes still take place even though inductance is present. The effect of the inductance is to introduce a time lag. It takes a finite amount of time for the current to change in response to a change in DC voltage. This time is a function of the ____________ and ____________ in the circuit.

31. (inductance, resistance) The time that it takes the current to rise to 63.2% of its maximum value is called the ____________ .

32. (time constant) The inductance and resistance in the circuit determine the time constant, which is expressed by the formula ____________ .

33. ($t = \frac{L}{R}$) An inductor with an inductance of 4.5 henrys and a resistance of 200 ohms is connected to a 9-volt DC source. The maximum circuit current is ____________ amperes.

34. (.045) Only the resistance of the inductor controls the current. Therefore you use Ohm's Law to compute it. $I = E/R = 9/200 = .045$ amperes. The time constant of this inductor is ____________ seconds.

35. (.0225) $t = L/R = 4.5/200 = .0225$ seconds or 22.5 ms. This means that it takes 22.5 ms for the current to rise to 63.2% of its maximum value or ____________ amperes.

36. (.02844) In 22.5 ms the current will rise to 63.2% of .045 amperes or $.632 \times .045 = .02844$ amperes. It will take __________ seconds for the current to rise to the maximum value.

37. (.1125) It takes five time constants (5t) for the current to rise to the maximum value or $5 \times .0225 = .1125$ seconds. The time constant also applies to the decay of current. It takes one time constant for the current to drop to 36.8% of the maximum value. With a maximum current of .045 amperes it takes 22.5 ms for the current to drop to __________ amperes.

38. (.01656) After one time constant, the current is $.368 \times .045 = .01656$ amperes. It will take five time constants for the current to drop to __________.

39. (zero)

INDUCTORS IN AC CIRCUITS

When an inductor is used in an AC circuit, it offers opposition to any change in current flow. An applied voltage that varies causes a counter emf to be continuously induced into the coil. The counter emf opposes the applied voltage, and the effect is to limit the amount of current flow in the circuit. Like a capacitor or resistor, the inductor opposes the flow of alternating current.

Due to the unique relationship between the applied voltage, induced voltage, and current in an inductive circuit, an inductor introduces a phase shift. The inductance causes the applied voltage and current are out of phase with one another.

Current-Voltage Relationship

Assume that a sine wave AC voltage is applied to an inductor as shown in Figure 4-9. Since the applied voltage is sinusoidal, the current flow in the inductor is also sinusoidal. The current through the coil periodically (every 180°) reverses direction. This reversal of current occurs because the applied voltage reverses polarity.

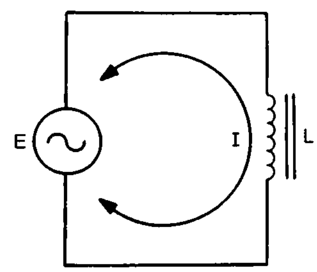


Figure 4-9
Sine-wave AC voltage applied to an inductor.

The current in this inductive circuit is illustrated by the current waveform in Figure 4-10. The changing current in the circuit causes the magnetic field around the inductor to rise and fall, which repeatedly cuts the turns of the coils and induces a voltage. The induced voltage, called the counter emf, opposes the applied voltage. The counter emf waveform is also illustrated in Figure 4-10. Note that the counter emf is out of phase (90° difference) with the current sine wave.

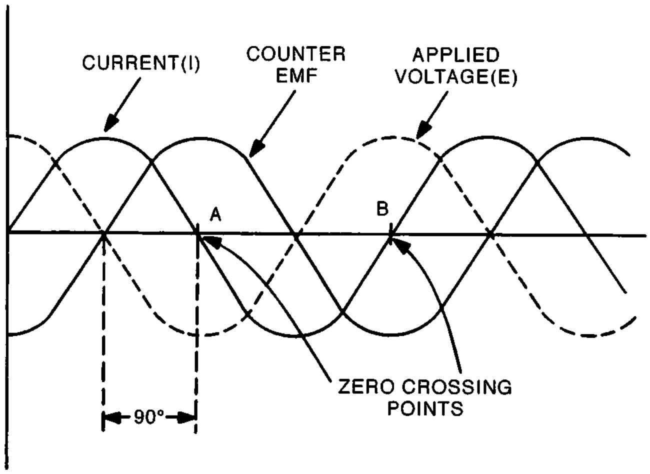


Figure 4-10
Current-voltage relationship in an inductive circuit.

As you recall from the previous description of self-induction, the amount of voltage that is induced into a conductor is proportional to the rate of change of the magnetic field. The faster the magnetic field expands or collapses, the higher the induced voltage. As you can see in Figure 4-10, the most rapid change in current occurs at points A and B. Here, the current changes from positive to negative or from negative to positive. The rate of change of current is highest at these points, and it is also at these points that the induced voltage is highest. The positive and negative peaks of the counter emf occur at the zero crossing points of the current waveform. The rate of change of current is zero at the positive and negative peaks of the current waveform. As a result, the induced voltage at these points is also zero. Note that, the counter emf is 90° out of phase with the current.

Counter emf opposes the applied voltage. Since the induced voltage is in direct opposition, it is exactly opposite in phase to the applied voltage. The applied voltage and the counter emf are 180° out of phase with one another. Keep in mind that one cycle of a sine wave represents 360°. One half cycle represents 180°, and one quarter of a cycle is 90°. As you can see from Figure 4-10, the induced and applied voltages are exactly opposite one another. When one is maximum, the other is minimum and vice versa. Also note that the current lags the applied voltage. As the applied voltage increases, the current increases 90° later

in time. When the applied voltage decreases, the current decreases 90° later. In a purely inductive circuit, current lags the applied voltage by 90°. This is sometimes stated as the voltage leads the current by 90°. This is opposite the voltage-current relationship in capacitive circuits.

Inductive Reactance

The counter emf that is induced into an inductor by a varying current opposes the applied voltage. As a result, the total effective voltage in the circuit is the difference between the applied voltage and the induced voltage. Because the induced voltage is less than the applied voltage, the effect of the inductance is to minimize or reduce current flow. The greater the inductance, the greater the counter emf. The opposition to current flow by an inductor in an AC circuit is called inductive reactance. Like resistance (R) and capacitive reactance (X_C), inductive reactance (X_L) is measured in ohms.

The amount of inductive reactance that is offered by a coil is directly proportional to its inductance and the frequency of the applied voltage. The greater the inductance, the greater the magnetic field. The greater the magnetic field, the higher the induced voltage for a given current. The higher the induced voltage, the greater the inductive reactance.

As the frequency of the applied AC voltage increases, the rate of change of current also increases. As the rate of change of current increases, the magnitude of the induced voltage becomes greater. This increased induced voltage causes greater opposition to the applied voltage.

Inductive reactance is represented by the symbol X_L. The inductive reactance in ohms is expressed by the formulas:

$$X_L = 2\pi fL$$

or

$$X_L = 6.28\ fL$$

In this formula, X_L is in ohms, f is the frequency in Hz, and L is the inductance in henrys. For example, to compute the inductive reactance of a .25 henry coil at 400 Hz, you make the following calculations:

$$X_L = 6.28\ fL$$

$$X_L = 6.28\ (400)\ (.25)$$

$$X_L = 628 \text{ ohms}$$

You can use simple algebra to rearrange the basic inductive reactance formula to solve for frequency or inductance.

$$f = \frac{X_L}{6.28\ L}$$

$$L = \frac{X_L}{6.28\ f}$$

Ohm's Law For Inductive Circuits

Ohm's Law applies equally to inductive AC circuits as it does to resistive or capacitive circuits. The current flow in an inductive AC circuit is directly proportional to the applied voltage and inversely proportional to the inductive reactance. The following expression represents this relationship mathematically:

$$I = \frac{E}{X_L}$$

In this expression, the current is in amperes, the voltage in volts, and the reactance in ohms. When the voltage increases or the reactance decreases, the current increases. When the applied voltage decreases or the reactance increases, the current decreases.

This relationship between the current, voltage, and reactance is illustrated in the following example.

How much current flows in a 2.5-millihenry choke when a 10 volt, 100 kHz sine wave is applied? To solve this problem, you must first compute the inductive reactance:

$$X_L = 6.28\ FL$$

$$X_L = 6.28\ (100{,}000)\ (.0025)$$

$$X_L = 1570 \text{ ohms}$$

Now that you know the inductive reactance and the applied voltage, you can use Ohm's Law to compute the circuit current:

$$I = \frac{E}{X_L} = \frac{10}{1570} = .00637 \text{ amperes or } 6.37 \text{ mA}$$

Mutual Inductance

The term inductance is more accurately described as self-inductance. This is the property of a coil whose magnetic field induces a voltage into itself. When the current in the coil varies, it produces a changing magnetic field. The magnetic lines of force cut the turns of the coil which produces the magnetic field. This induces a voltage into itself, that opposes the applied voltage, and is referred to as self-induction.

The varying magnetic field that surrounds an inductor can also influence other nearby conductors. As the magnetic field varies, the lines of force can cut the turns of an adjacent coil and induce a voltage into it as well as into the inductor that produces the field. The process by which one inductor causes a voltage to be induced into another is called mutual induction.

Figure 4-11 shows an inductor, with the primary coil (the coil closest to the voltage source), connected to an AC voltage source. When current flows in the primary coil, it produces a varying magnetic field. This causes a voltage to be induced into the primary coil itself as well as into the secondary coil. Note that the secondary coil is not directly connected to the source voltage. The magnetic lines of force cut the turns of an adjacent (secondary) inductor, and induce a voltage into it. The induced voltage causes current to flow through the load resistor.

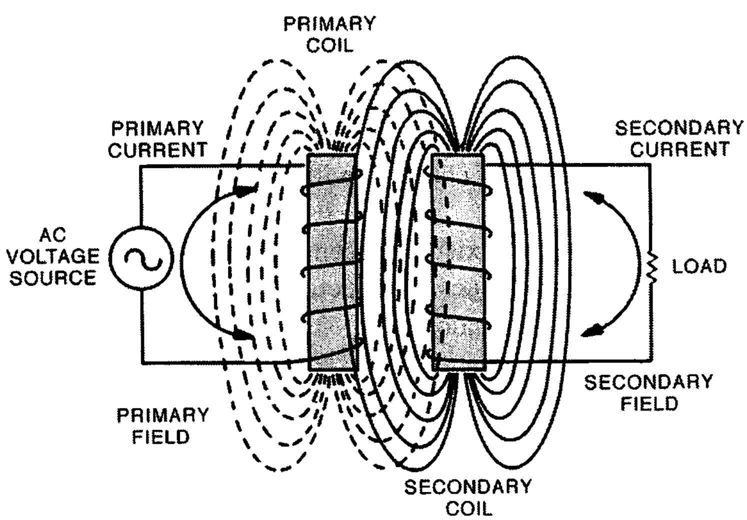


Figure 4-11
Mutual inductance
between adjacent coils.

When current begins to flow in the secondary coil, it produces a varying magnetic field around it. This magnetic field induces a voltage into the secondary coil. The varying magnetic field from the secondary coil also induces a voltage back into the primary winding. As you can see, there are four induced voltages

that affect the operation of the circuit. These are the two self-induced voltages and the two mutually-induced voltages. The overall effect is complex due to the interrelationship between the magnetic fields.

The two coils in Figure 4-11 have mutual inductance because one coil induces a voltage into the other. Mutual inductance is designated by the symbol L_m. The unit of mutual inductance is the henry. A mutual inductance of one henry is defined as the condition where a current change of one ampere per second in one coil, induces a voltage of one volt into another coil.

The amount of mutual inductance that exists between two adjacent coils depends upon the degree of coupling between them. In other words, mutual inductance is determined by how many lines of force from one coil cut the turns of an adjacent coil. The degree of coupling between the coils is expressed by a factor called the coefficient of coupling, k. A coefficient of coupling of one, $k = 1$, represents 100% coupling of the magnetic lines of force.

When all of the magnetic lines of force that are produced by one coil do not cut all of the turns of the other coil, the coefficient of coupling is less than 1. The worst case situation is where none of the magnetic lines of force that are produced by one coil cut the turns of the other coil. In this case, the coefficient of coupling is zero.

The coefficient of coupling is zero when the two coils are spaced far enough apart so that their magnetic fields do not influence each other. When the two coils are at right angles to each other, the magnetic lines of force of one coil do not influence the other. For other combinations of spacing and relative positions of the coils, the coefficient of coupling will be between 0 and 1.

The mutual inductance that exists between two coils is a function of the coefficient of coupling and the values of inductance of the two coils. Mutual inductance is expressed by the equation:

$$L_m = k\sqrt{L_1 L_2}$$

Mutual inductance only occurs where the magnetic lines of force that are produced by one coil can affect another adjacent coil. In some situations, no mutual inductance is possible. For example, when you use two iron-core chokes, the coefficient of coupling between them is zero or very close to it. The iron-core in an inductor concentrates the lines of force and prevents them from extending outward beyond the coil. This is particularly true in iron-core chokes that have a completely closed loop core. None of the magnetic lines of force leave the core. The property of mutual inductance is generally associated with coils that are on a common core or closely spaced air-core coils.

Inductors in Series and in Parallel

Inductors are often connected in series or parallel combinations to produce different values of inductance. The rules that determine the total inductance of series and parallel connected inductors are the same as the rules you use to compute total resistance of resistors that are connected in series and in parallel.

SERIES INDUCTANCE

When two or more inductors are connected in series, the total inductance of the combination is the sum of the individual inductances. Figure 4-12 shows three inductors that are connected in series. The total inductance of this combination is:

$$L_T = L_1 + L_2 + L_3$$

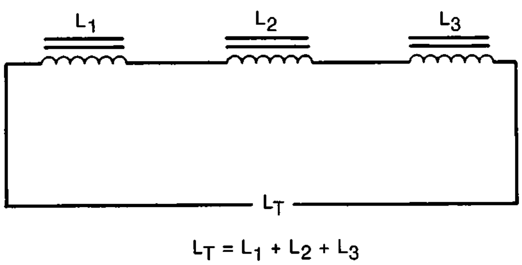


Figure
Inductors in series.

The calculation assumes that no mutual inductance exists between the inductors. When mutual inductance is involved, total inductance of the combination is the sum of the individual inductance values plus the value of mutual inductance.

When two inductors are connected in series in such a way that their magnetic fields aid one another, the total inductance of the combination is as expressed by the formula:

$$L_T = L_1 + L_2 + 2\,L_m$$

When two coils are connected in series so that their magnetic fields oppose one another, the total inductance of the combination is expressed by:

$$L_T = L_1 + L_2 - 2\,L_m$$

In both situations where mutual inductance is present, the magnetic lines of force of one coil affect those of the other. The directions of the magnetic fields are important because they can aid or oppose each other. You can determine the directions of the magnetic fields if you know the direction in which the coils are wound. When the series connected coils are wound so that their turns are all in the same direction, the magnetic fields add. In this case, the magnetic fields are series-aiding. When the turns of two series-connected coils are wound in opposite directions, the magnetic fields oppose each other. In this case, there is some cancellation of the magnetic effect between the two coils. When it is desirable to minimize or reduce the mutual inductance to zero, series-connected coils should be positioned so that they are at right angles (perpendicular) to each other.

PARALLEL INDUCTANCE

When two inductors are connected in parallel as shown in Figure 4-13, the formula for total inductance is:

$$L_T = \frac{L_1 \times L_2}{L_1 + L_2}$$

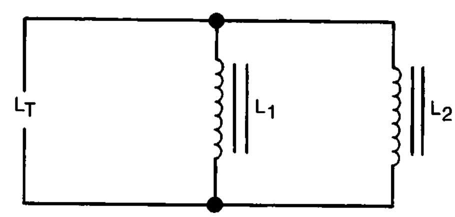


Figure 4-13
Inductors in parallel.

This expression is similar to the formula for parallel resistors or series capacitors. When more than two inductors are connected in parallel, you can determine the total inductance of the combination with the above expression by combining the inductors two at a time until you obtain the total. This expression assumes that no mutual inductance exists. The reciprocal method that you use to find R_T can also be used to solve for L_T, for a circuit that contains any number of inductors in parallel.

The Quality of an Inductor

Until now, this unit assumed that an inductor is perfect. A perfect inductor or a purely inductive circuit has no resistance. In a purely inductive AC circuit, the only opposition to current flow is the inductive reactance. However, from a practical standpoint, perfect components do not exist. Since the inductor is a coil of wire, it has resistance. The resistance of an inductor is the specific resistance of the wire that is used to manufacture the coil. It is not unusual for a choke (coil or inductor) to have a resistance of several hundred ohms.

In many circuits, the resistance of the inductor is so low that you can consider it as negligible. In these cases, it has little or no effect on the operation of the circuit. In other applications, the resistance of the inductor is higher, it can greatly affect the operation of the circuit.

Low resistance is a desirable characteristic of an inductor. The primary reason for this is that a resistance dissipates power. Therefore, power is dissipated by an inductor due to its resistance. An inductors resistance basically determines the quality of an inductor. The quality or figure of merit of an inductor is called its Q. The Q of a coil is the ratio of the energy that is stored in the coil in the form of a magnetic field to the energy dissipated in its resistance. This is expressed as:

$$Q = \frac{\text{energy stored}}{\text{energy dissipated}}$$

Since the inductance and inductive reactance is a measure of the amount of energy that is stored in a coil, and since the resistance of a coil is a measure of the amount of energy dissipated, you can also express the Q of a coil as the ratio of the inductive reactance to the resistance.

$$Q = \frac{X_L}{R}$$

For example, the Q of a 88 mH coil with a resistance of 50 ohms at 10 kHz is:

$$X_L = 6.28\ fL$$

$$X_L = 6.28\ (10{,}000)\ (.088)$$

$$X_L = 5526.4 \text{ ohms}$$

$$Q = \frac{X_L}{R} = \frac{5{,}526.4}{50} = 110.528$$

Q is a figure of merit and is expressed as a numerical value without a unit of measure. It is simply a ratio.

This relationship is widely used to indicate the quality of an inductor. Generally, the higher the Q the better the coil. A high Q coil has a Q of approximately 20 or greater.

Since Q is directly proportional to the inductive reactance, Q increases as frequency increases. The reactance is essentially a constant at low frequencies. Due to certain electrical characteristics, the resistance of an inductor increases as frequency increases. However, the resistance does not increase as rapidly as inductive reactance. Therefore, Q increases with frequency.

Programmed Review

40. When you apply an AC voltage to an inductor, alternating current flows. The varying current produces a varying magnetic field that ___________ a voltage into the inductor.
41. (induces) If the current is sinusoidal, the induced voltage is ___________.
42. (sinusoidal) The induced voltage is 180° out of phase with the applied voltage. In other words, the self-induced voltage ___________ the applied voltage.
43. (opposes) The rate of change of current determines the amplitude of the induced voltage. The faster the current changes, the higher the induced voltage. At the peaks of the current waveform, the rate of change of current is ___________.
44. (zero) At the current peaks, the rate of change of current is zero. At this time the induced voltage is ___________.
45. (zero) The greatest rate of change of current occurs when the current waveform is ___________.
46. (zero or crossing zero) The induced voltage is at its peak during this time. Due to this relationship between the current and induced voltage, their maximum, minimum, and zero crossing points do not coincide. This condition is referred to as ___________.
47. (phase shift) The current and induced voltage are 90° out of phase with each other in a pure inductance. The current and applied voltage are also ___________ degrees out of phase with each another.
48. (90) The current ___________ the applied voltage.

49. (lags) Or, the applied voltage __________ the current.
50. (leads) The opposition offered to the flow of AC by an inductor is called __________ __________.
51. (inductive reactance) Inductive reactance is represented by the designation __________.
52. (X_L) The unit of inductive reactance is the __________.
53. (ohm) Like resistance, capacitive reactance and impedance, inductive reactance is measured in ohms since it is an opposition to current flow. The inductive reactance is a function of two factors __________ and __________.
54. (frequency, inductance) The higher the frequency of the applied voltage, the greater the rate of change of current and the higher the induced voltage. The greater the induced voltage, the greater the opposition to __________.
55. (current) The greater the inductance, the greater the magnitude of the induced voltage for a given current. This means a higher induced voltage and greater opposition to current flow. The __________ __________ is directly proportional to frequency and inductance.
56. (inductive reactance) You can compute the inductive reactance with the formula __________.
57. (X_L = 6.28 fL) If the frequency is 2 kHz and the inductance is 9 mH, the inductive reactance is __________ ohms.
58. (1130.4 X_L = 6.28 (2000) (.09) = 1130.4 ohms) The current flow in an inductive circuit is influenced by the frequency and inductance. If you decrease the frequency, the current will __________.

59. (increase) When the frequency decreases, the inductive reactance and the opposition to current flow also decrease. Therefore, the current will increase. Increasing the inductance causes the current to ________.

60. (decrease) When the inductance increases, the reactance increases and therefore decreases the current. The formula which relates the current, voltage, and reactance in an inductive circuit is I = ________.

61. ($\frac{E}{X_L}$) Self-inductance refers to the effect of a self-induced voltage that is created by a current change. The effect of one inductor inducing a voltage into another is referred to as ________ ________.

62. (mutual inductance) The magnetic field that is generated by a coil in duces a voltage into itself as well as any closely adjacent coil. The amount of voltage that is induced into a nearby coil is a function of the relative spacing and position of the two coils. The degree to which the magnetic lines of force of one coil affect the other coil is called the ________ ________ ________.

63. (coefficient of coupling) If all of the lines of force of one coil cut all of the turns of the other, the coefficient of coupling is ________.

64. (1) If none of the lines of force of one coil cut the turns of the other, the coefficient of coupling, k, is ________.

65. (0) The mutual inductance L_m is a function of the individual coil inductances and the ________ ________ ________.

66. (coefficient of coupling) The mutual inductance is expressed by ________.

67. ($L_m = k\sqrt{L_1 L_2}$) When inductors are connected in series, the total inductance of the combination is the ________ of the individual inductances.

68. (sum) The total inductance (L_T) of a 750-mH choke (L_1) and a 1.2 H choke (L_2) in series is __________ H.

69. (1.95 $L_T = L_1 + L_2 = .75 + 1.2 = 1.95$ H). This relationship assumes that there is no __________ __________ between the coils.

70. (mutual inductance) If mutual inductance is involved, the total series inductance will be different from the simple sum. If the magnetic fields of the two coils add, the total inductance will be __________________.

71. ($L_T = L_1 + L_2 + 2\,L_m$) If the two magnetic fields oppose each other, the total inductance will be ____________.

72. ($L_T = L_1 + L_2 - 2\,L_m$) If two inductors, L_1 and L2, are connected in parallel, the total inductance is L_T __________.

73. ($\frac{L_1 L_2}{L_1 + L_2}$) Again, this assumes that no mutual inductance exists. The term __________ is used to describe the quality of an inductor.

74. (Q) Q is the ratio of the inductive reactance of a coil to its resistance. Expressed mathematically, this is __________.

75. ($Q = \frac{X_L}{R}$) The Q of a 50-mH inductor at 75 kHz with a resistance of 80 ohms is __________.

76. (294 $X_L = 6.28\,fL = 6.28\,(75000)\,(.05) = 23550$ ohms. $Q = X_L/R = 23550/80 = 294$.) The higher the Q, the better the coil. A coil with a Q of __________ or more is considered to be a high Q coil.

77. (20)

RL Circuits

The most commonly used inductive circuit is a series-connected resistor and inductor. This combination is called an RL circuit. Even a circuit that contains only an inductor is a series RL circuit due to the resistance of the inductor. In this section, you will analyze the operation and characteristics of a series RL circuit.

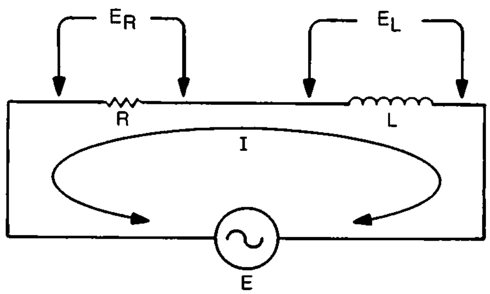


Figure 4-14
A series RL circuit.

Series RL Circuits

Figure 4-14 shows a resistor and inductor in series with an AC voltage source. The current flow in the circuit causes voltage drops to be produced across the inductor and the resistor. These voltages are proportional to the current in the circuit and the individual resistance and inductive reactance values. The resistor voltage E_R, and the inductor voltage, E_L, expressed in terms of Ohm's Law are:

$$E_R = IR$$

$$E_L = IX_L$$

For this discussion, assume that the inductor is a perfect inductance. That is, the inductor has no resistance. In this example, all of the resistance in the circuit is represented by the resistor R.

Because this is an inductive circuit, the current flow in the circuit lags the applied voltage. In a purely resistive circuit the current and voltage are in phase. In a purely inductive circuit, the current lags the applied voltage by 90°. In a series RL circuit, the current lags the applied voltage by some phase angle between 0° and 90°. The amount of phase shift is a function of the values of the resistor and the inductive reactance.

As in any series electrical circuit, the sum of the voltage drops across the various elements in the circuit equals the applied voltage. In a circuit which contains a reactive component, such as an inductor, the sum of the voltages must be a vector sum due to the phase shift in the circuit.

Vector Diagrams

As in a series RC circuit, you can use a vector diagram to show the relationship between the current and voltages in a series RL circuit. The vectors represent voltage and current amplitudes in the circuit. The directions of the vectors indicate the phase relationships.

Figure 4-15 shows a vector diagram of a series RL circuit. The reference vector is labeled I and represents the currents in the circuit. Current is common to all circuit elements in a series circuit. The voltage across the resistor is in phase with the current flowing through it. Therefore, the resistor voltage vector, E_R coincides with the current vector as shown.

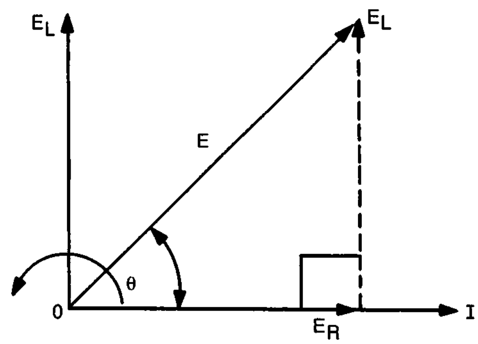


Figure 4-15
Vector diagram of a series RL circuit.

The voltage across the inductor leads the current by 90°. In other words, the circuit current lags the voltage across the inductor by 90°. Therefore, the inductive voltage vector, E_L, is shown 90° out of phase (leading) with the current vector.

Recall that you assume that each of the vectors in the diagram rotates in the counterclockwise direction around the origin. The rotation of the vectors represents the variations of voltages and currents, in a sinusoidal manner, for a given period of time. One complete rotation represents one AC cycle. With the counterclockwise direction of rotation, you can see that the inductor voltage is ahead of (leading) the current vector. Another way to look at this is that the current vector lags the inductive voltage vector by 90°.

The applied voltage is the vector sum of the resistor and inductor voltages. To find this vector sum, use the resistor voltages as one side and the inductor voltages as the other side to form a right triangle. The applied voltage, E, is the

hypotenuse. Note that the applied voltage leads the current by an angle that is between 0° and 90°. Since you know the resistor and inductor voltages, you can solve for the hypotenuse of the right triangle to find the applied voltage. You can do this with the Pythagorean Theorem. The formula for the applied voltage is:

$$E = \sqrt{(E_R)^2 + (E_L)^2}$$

When you rearrange the above formula, you can compute either the resistor or inductor voltages if you know the applied voltage and the remaining voltage. These formulas are:

$$E_R = \sqrt{(E)^2 - (E_L)^2}$$

$$E_L = \sqrt{(E)^2 - (E_R)^2}$$

The following examples show you how to use these formulas.

1. In a series RL circuit, the resistor voltage is 15 volts and the inductor voltage is 18 volts. What is the applied voltage?

$$E = \sqrt{(E_R)^2 + (E_L)^2}$$

$$E = \sqrt{(15)^2 + (18)^2}$$

$$E = \sqrt{225 + 324}$$

$$E = \sqrt{549} = 23.43 \text{ volts}$$

2. The AC voltage applied to a series RL circuit is 80 volts. The resistor voltage drop is 32 volts. What is the inductor's voltage?

$$E_L = \sqrt{(E)^2 - (E_R)^2}$$

$$E_L = \sqrt{(80)^2 - (32)^2}$$

$$E_L = \sqrt{6400 - 1024}$$

$$E_L = \sqrt{5376} = 73.32 \text{ volts}$$

Impedance

The impedance of an RL circuit is the total opposition to current flow that is offered by both the resistor and the inductor. The applied voltage and total circuit current determine the circuit's impedance. According to Ohm's Law:

$$Z = \frac{E}{I}$$

Impedance is a function of the resistance and the inductive reactance and you can calculate it with the formula:

$$Z = \sqrt{(R)^2 + (X_L)^2}$$

The impedance of a series RL circuit is the square root of the sum of the squares of the resistance and the inductive reactance. Impedance, like resistance and inductive reactance, is expressed in ohms. You can rearrange the basic formula to solve for the resistance or the reactance in terms of the other two factors.

$$R = \sqrt{(Z)^2 - (X_L)^2}$$

$$X_L = \sqrt{(Z)^2 - (R)^2}$$

You should recognize that the basic impedance formula is the Pythagorean Theorem. Therefore you can use the sides of a right triangle to represent the resistance, inductive reactance, and total impedances. This is illustrated in Figure 4-16.

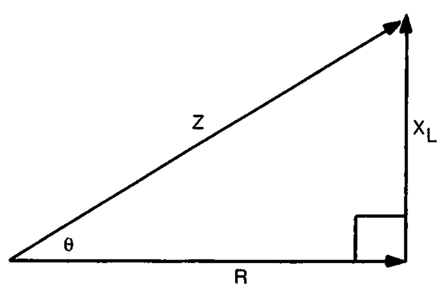


Figure 4-16
Impedance triangle
of a series RL circuit.

This vector diagram is similar to the voltage vector diagram that you encountered earlier. Since the resistor and inductor voltages are directly proportional to the value of the resistor and the inductor's inductive reactance, the impedance and voltage vector diagrams are proportional. The angle between the impedance

and the resistance is the phase angle of the circuit. It indicates the amount the circuit current lags the applied voltage. The following examples show you how to use the impedance formulas.

1. What is the impedance of a 1.5-henry choke with 200 ohms of resistance at 60 Hz?

$$X_L = 6.28\ fL$$

$$X_L = 6.28\ (60)\ (1.5) = 565.2 \text{ ohms}$$

$$Z = \sqrt{(R)^2 + (X_L)^2}$$

$$Z = \sqrt{(200)^2 + (565.2)^2}$$

$$Z = \sqrt{40000 + 319451}$$

$$Z = \sqrt{359451} = 599.5 \text{ ohms or approximately } 600 \text{ ohms}$$

2. In a series RL circuit, the resistor voltage is 20 volts and the applied voltage is 32 volts at 400 Hz. The resistance is 1000 ohms. What is the inductance of the coil?

$$I = \frac{E_R}{R} = \frac{20}{1000} = .02 \text{ amperes}$$

$$Z = \frac{E}{I} = \frac{32}{.02} = 1600 \text{ ohms}$$

$$X_L = \sqrt{(Z)^2 - (R)^2}$$

$$X_L = \sqrt{(1600)^2 - (1000)^2}$$

$$X_L = \sqrt{256000 - 1000000}$$

$$X_L = \sqrt{1560000} = 1249 \text{ ohms}$$

If $X_L = 6.28\ fL$:

$$L = \frac{X_L}{6.28\ f}$$

$$L = \frac{1249}{6.28\ (400)} = \frac{1249}{2512} = .496 \text{ H}$$

Phase Shift

The phase shift in a series RL circuit is some value between 0° and 90°. The actual value of the phase shift is a function of the resistance and inductive reactance. The phase angle is illustrated in Figure 4-15 and 4-16. The phase shift in a series RL circuit is a function of the tangent in the voltage and impedance triangles. The tangent is the ratio of the opposite side divided by the adjacent side. In Figure 4-16, the tangent is the ratio of the inductive reactance (opposite side), to the resistance (adjacent side). Expressed mathematically this is:

$$\tan \theta = \frac{X_L}{R}$$

Since current is the same in both the resistor and the inductor, the voltages dropped across them are directly proportional to the resistance and reactance values. Therefore, you can use the inductor and resistor voltages to determine the tangent of the phase angle. This is expressed mathematically as:

$$\tan \theta = \frac{E_L}{E_R}$$

To find the phase shift in a series RL circuit, determine the resistance and reactance values, or the resistor and inductor voltage drops. Compute the ratio of the inductive reactance to the resistance. Look that value up in a table of trigonometric functions. The function tables are located in Appendix C at the end of Unit 3. Look up the numerical value of the ratio in the Tangent column, and locate the closest angle that corresponds to the value in the Degrees column.

An important point to remember is that the tangent of 45° is equal to one. Many times in electronics it is desirable to make the resistive and reactive values equal. The value of both the sine and cosine at an angle of 45° is equal to .707.

The following example demonstrates how to compute phase angle. What is the phase shift that is produced by a 1.5 henry choke with a resistance of 200 ohms, at a frequency of 60 Hz?

$$X_L = 6.28fL = 6.28\ (60)\ (1.5) = 565.2 \text{ ohms}$$

$$\tan \theta = \frac{X_L}{R}$$

$$\tan \theta = \frac{565.2}{200}$$

$$\tan \theta = 2.826$$

From Appendix C, the tangent of 70° = 2.748 and the tan of 71° = 2.904. Therefore the angle that corresponds to a tangent of 2.826 is between 70° and 71°, or about 70.5°.

Power in an Inductive Circuit

The only power that is actually dissipated in a series RL circuit is the power dissipated by the resistance. To compute true power dissipation, you can use any of the three standard power formulas:

$$P = EI$$

$$P = I^2R$$

$$P = \frac{E^2}{R}$$

The inductor, like the capacitor, is a reactive component that does not dissipate power in its pure form. The inductor alternately stores energy in the form of a magnetic field and then releases it. During one half cycle of AC operation, storage of electrical energy occurs in the magnetic field that is built around the inductor. When the magnetic field collapses, it induces a voltage into the inductor. This self-induced voltage then acts as a source that provides energy to the circuit. The consumption and release of energy cancel each other which makes the total average power that is dissipated by the inductive reactance zero. Figure 4-17 shows the current, voltage, and power relationships in a purely-inductive circuit.

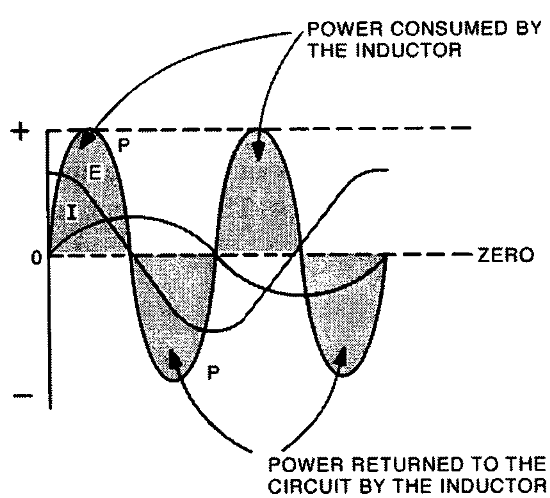


Figure 4-17
Power dissipation
in a pure inductance.

Unlike a capacitor, however, an inductor has resistance. For that reason, an inductor actually dissipates some power. It is the resistive portion of the inductor that causes the power to be dissipated. This is called true power. Figure 4-18 shows the current, voltage, and power curves of a series RL circuit where the phase angle is 45°. The power curve, above the zero line, represents the power that is dissipated in the resistance (true power) and the power that is consumed by the inductance. The power curve below the zero line is the power that the inductance returns to the circuit.

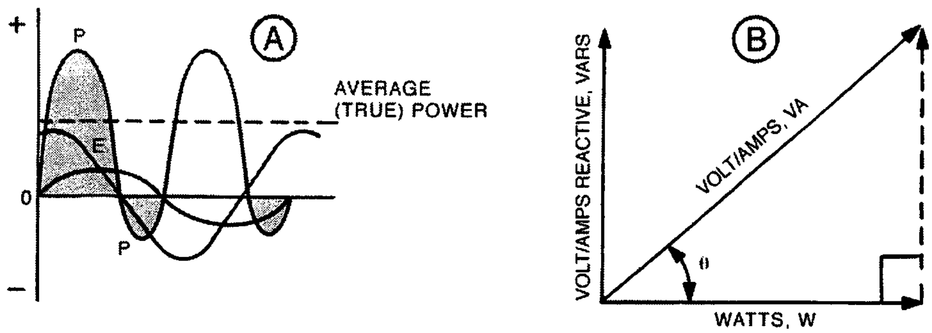


Figure 4-18
Power dissipation in a series RL circuit with a 45° phase shift.

Figure 4-18B shows a power vector diagram for a series RL circuit. True power, the power that is actually dissipated by the resistive portion of the circuit, is given in watts and is shown as the adjacent side of angle theta.

The volt/amps reactive is the power in the inductive portion of the circuit that the inductor both produces and uses. This power is shown in Figure 4-18A as the power below the zero line. In Figure 4-18B, this value is shown as the side opposite angle theta.

The vector sum of true power in watts and the volt/amps reactive is the apparent power that is measured in volts/amps. The apparent power is indicated as the hypotenuse of the power triangle.

Voltage, Impedance, and Power Relationships in RL Circuits

When you studied RC parallel circuits, you learned that there is a relationship between the voltage, impedance. and power vector diagrams. The same relationship holds true for vector diagrams of RL circuits. This is illustrated in Figure 4-19.

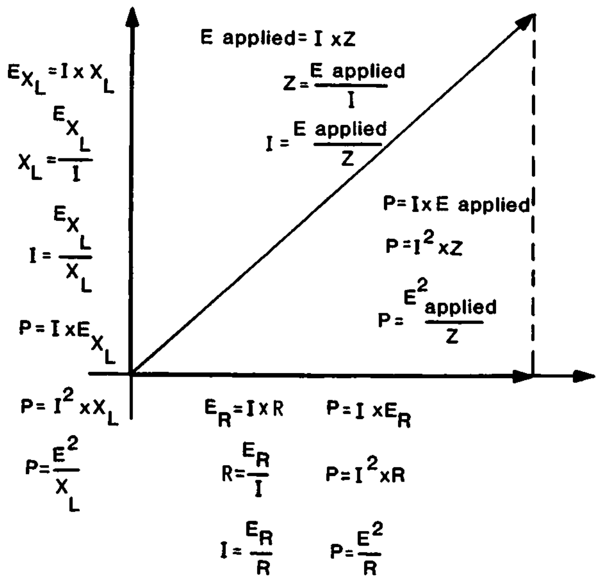


Figure 4-19

Although it is shown as only one triangle, the sides of this triangle actually represent three different triangles. The three triangles represent voltage, impedance, and power. The mathematical relationship that unites these three triangles into one is Ohm's Law. Ohm's Law, and its variations, apply to the sides of the triangles. For example, if you know the circuit current and the resistance of the circuit, you can determine the voltage drop across the resistance with the formula:

$$E_R = I \times R$$

You can find the applied voltage in the same way with this variation of Ohm's Law:

$$E_A = I \times Z$$

You can use Ohm's Law to find any quantity on any side of this triangle.

In addition, the phase shift that you determined with quantities from any of the triangles, applies to all of the triangles. All three triangles relate to the same circuit. Therefore, the phase shift that is indicated by all three triangles must be the same. Following is a problem that demonstrates these concepts.

Draw a vector diagram for a circuit with a resistance of 40 ohms, an inductive reactance of 30 ohms, and a circuit current of .1 amperes. The phase angle of the circuit is about 37°.

With the information you are given, you can quickly determine the voltage drop across the inductive reactance and resistance in the circuit. Just apply Ohm's Law like this:

$$E_R = .1A \times 40 \text{ ohms or } 4 \text{ volts}$$

and

$$E_{X_L} = .1A \times 30 \text{ ohms} = 3 \text{ volts.}$$

Once you have calculated these two voltages, use the Pythagorean Theorem to determine the applied voltage:

$$E_{applied} = \sqrt{4V^2 + 3V^2} = 5V$$

You can now find the circuit impedance with the Ohm's Law derivation:

$$Z = \frac{E_{applied}}{I} = \frac{5V}{.1A} = 50 \text{ ohms}$$

Now, you can apply the power formulas and you can determine the three sides of the power vector diagram:

$$P = I \times E_R$$
$$P = .1A \times 4V$$
$$P = .4\ W$$

and:

$$P = I \times E_{X_L}$$
$$P = .1A \times 3V$$
$$P = .3 \text{ VARS}$$

and:

$$P = I \times E_A$$
$$P = .1A \times 5V$$
$$P = .5 \text{ VA}$$

As you can see, once you have solved the vector diagram for any one triangle, it is a simple matter to apply Ohm's Law to determine all of the other quantities that are necessary to analyze the circuit.

Parallel RL Circuits

Another type of inductive circuit is the parallel RL circuit. A basic RL circuit is shown in Figure 4-20. Notice that this circuit is no more than a coil and a resistor that are connected in parallel. Although the coil itself has some internal resistance, this resistance is ignored in the following discussion.

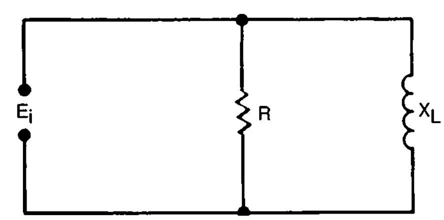


Figure 4-20

As you should recall from your study of DC electronics, in a parallel circuit the source or applied voltage is dropped across each of the branches of the circuit. In addition, in a parallel circuit, the resistance of the entire circuit is always less than the resistance of the smallest branch in the circuit. These are important points when you analyze a parallel RL circuit. Here's why.

First, since the voltage across each of the branches is equal to the source voltage, you use voltage as the reference when you construct a vector diagram for parallel RL circuits. Although the voltage across each branch is the same, the current through each branch varies according to the amount of opposition to current flow

in that branch. Also, current through the inductive branch lags the current through the resistive branch. The inductive current lags by an angle of less than 90°. Figure 4-21 shows a typical vector diagram for a parallel RL circuit.

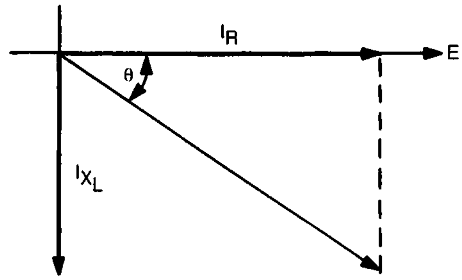


Figure 4-21

Because the impedance of a parallel circuit is always less than either the resistance or the inductive reactance of the circuit, it is not possible to construct an impedance triangle, unless you use the reciprocal values for resistance, inductive reactance, and impedance. Here's an example:

Assume that you have an RL circuit where the resistance is 50 ohms and the inductive reactance is 50 ohms. To determine the impedance of the circuit, you can use the Pythagorean Theorem. Remember to use reciprocal values like this:

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_?}\right)^2}$$

$$\frac{1}{Z} = \sqrt{.02^2 + .02^2}$$

$$Z = 35.35 \text{ ohms}$$

The impedance vector diagram is shown in Figure 4-22.

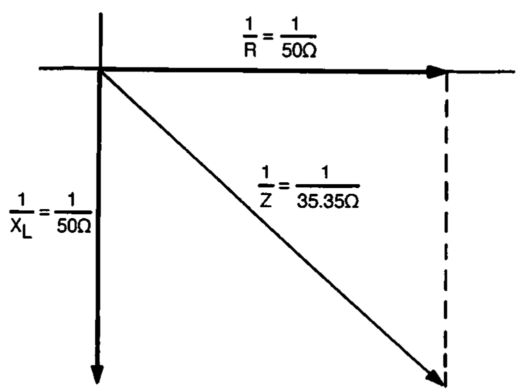


Figure 4-22

You can also find impedance in a parallel RL circuit with a variation of the product over the sum formula. The impedance equation is:

$$Z = \frac{R \times X_L}{\sqrt{R^2 + X_L{}^2}}$$

You may recognize this formula from the preceding unit. In fact, everything you learned so far for the RL parallel circuit is a repetition of the formulas that were presented for the RC parallel circuits. This is because the mathematical theory is identical. The difference between parallel RC and parallel RL circuits is that, in an RC circuit the current leads the voltage while in an RL circuit the current lags the voltage. All Ohm's Law and vector diagram relationships that apply to RC circuits also apply to the RL circuits. With this in mind, if you have any further questions in regard to RL parallel circuits, simply refer to the section on RC parallel circuits in Unit 3.

You may find it easier to solve for individual branch currents and plot the vector relationships in the form of current vectors. The important thing to remember is that you use current as the reference in series circuits. In addition, you use voltage as the reference in parallel circuits. The important point is that you always use the values that are constant as the reference.

Programmed Review

78. When current flows in a series RL circuit, voltage drops are developed across the resistance and the inductance. These voltage drops can be computed with ___________ Law.

79. (Ohm's) If you know the current (I), the resistance (R) and inductive reactance (X_L), you can compute the resistor voltage (E_R) and inductor voltage (EL) with the expressions ___________ and ___________.

80. (ER = IR, $E_L = IX_L$) As in any series circuit, the sum of the voltage drops is equal to the applied voltage (E). However, this is not a direct sum. Instead it is a ___________ sum.

81. (vector) The current and resistor voltage are in phase, but the current and inductor voltage are 90° out of phase. Because of this phase shift, you cannot add the two voltages directly. You must use the vector sum. You do this with Pythagorean's theorem. The applied voltage is ___________.

82. ($E = \sqrt{(E_R)^2 + (E_L)^2}$) If the resistor voltage is 9 volts and the inductor voltage is 12 volts, the applied voltage is ___________ volts.

83. ($E = \sqrt{9^2 + 12^2} = \sqrt{81 + 144} = \sqrt{225} = 15$ volts) The total opposition to current flow in an RL circuit is called ___________.

84. (impedance) The impedance is a function of the ___________ and ___________ ___________.

85. (resistance, inductive reactance) These factors are related by the formula ___________.

86. ($Z = \sqrt{R^2 + X_L^2}$) What is the impedance of a 250-mh choke with a resistance of 385 ohms at 2 kHz? Z = ___________ ohms.

87. [3163.5 250 mH = .25 H, 2 kHz = 2000 Hz $X_L = 6.28\ fL = 6.28$ (2000) (.25) = 3140 ohms $Z = \sqrt{R^2 + X_L^2} = \sqrt{385^2 + 3140^2}$ $Z = \sqrt{148225 + 9859600} = Z = \sqrt{10007825} = 3163.5$ ohms.] If 6 volts AC is applied to this choke the current is __________ amperes.

---

88. (.0019 $I = \frac{E}{Z} = \frac{6}{3163} = .00189$ or .0019 amperes) The total circuit current is a function of the applied voltage (E) and the circuit current (I) as expressed by Ohm's Law:

$$I = \frac{E}{Z}$$

Therefore, you can express the total circuit impedance in terms of the current and applied voltage. Z = __________.

---

89. ($Z = \frac{E}{I}$) The phase shift in a series RL circuit is a function of the __________ and __________ __________.

---

90. (resistance, inductive reactance) In a purely resistive circuit, the phase angle between the current and applied voltage is __________.

---

91. (0°) In a purely inductive circuit, the current and applied voltage are __________ out of phase.

---

92. (90°) In an RL circuit, the phase angle is between __________ and __________.

---

93. (0°, 90°) As the resistance increases relative to the inductive reactance, the phase shift __________.

---

94. (decreases or approaches 0°) When the inductive reactance increases relative to the resistance, the phase shift approaches __________.

95. (90°) In an inductive circuit the current __________ the applied voltage.

96. (lags) You can compute the phase angle θ in a series RL circuit with the formula tan θ = __________.

97. ($\frac{X_L}{R}$) What is the phase shift that is produced by the choke described in frame 86? θ = __________. (Use Appendix C in Unit 3.)

98. (83° $\tan\theta = \frac{X_L}{R} = \frac{3140}{385} = 8.16$, θ equals approximately 83°). The power that is dissipation in an inductive circuit occurs in the __________ part of the circuit.

99. (resistive) Power is dissipated only in the resistance. This is called the __________ power.

100. (true) You can use any of the standard power formulas to compute the dissipation. What power is dissipated in the choke described in frames 86, 87, and 88? P = __________ watts.

101. [.001386 $P = I^2R = (.0019)^2\ 385 = .001386$ watts or 1.386 milliwatts] In a pure inductance the power dissipation is __________.

102. (zero)

EXPERIMENT 6

RL Circuits

OBJECTIVES: *To describe how an induced voltage and current can affect a neon lamp.*

To construct a series RL circuit.

To compare the calculations of a series RL circuit with measured values and determine the impedance of the circuit.

To verify that when you change the inductance of a coil, by moving it's core, the voltage dropped across the coil will change.

To observe a Lissajous pattern, and use this information and Trigonometric functions to identify an AC phase angle.

Materials Required

Heathkit Analog Trainer
Oscilloscope
AC voltmeter
1—Variable inductor (#45-610)
2—1 kΩ, 1/2-watt resistor (brown-black-red)
1—Neon lamp
1—Alignment tool
2—2" lengths of #22 hookup wire

Procedure

1. Cut two 2-inch lengths of #22 hookup wire. Strip 3/8 inch insulation from each end of each wire. Solder one end of each wire to the two terminals on the variable inductor, #45-610 as shown in Figure 4-23.

   The variable inductor has a movable ferrite core. You can see this core if you look into the open end of the inductor. The core has a hex (6-sided) hole in the center and is threaded so that, as you turn it, moves within the coil. You can change its position with respect to the coil winding, which changes the inductance of the coil. Later, you will use a plastic alignment tool to adjust the core. You can insert the hex-shaped end of the alignment tool into either end of the inductor to make the adjustment. See Figure 4-23.

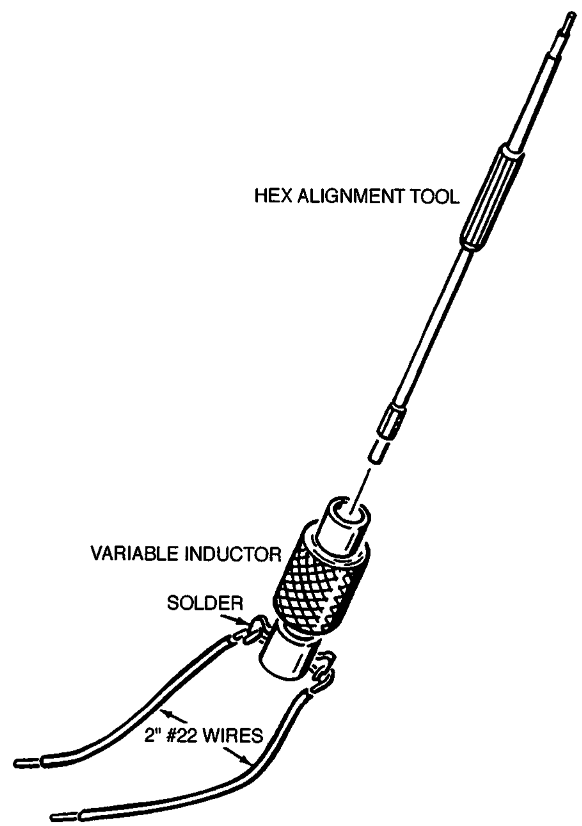


Figure 4-23

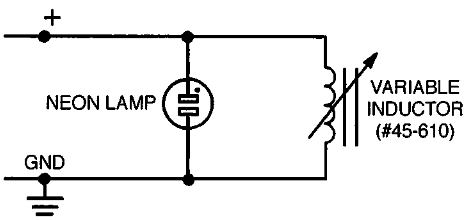


Figure 4-24

2. Construct the experimental circuit shown in Figure 4-24. Connect the variable inductor in parallel with the neon lamp on the breadboard of the Trainer. Then connect a DC voltage to the choke as indicated. The pictorial wiring diagram for this circuit is shown in Figure 4-25. Leave the lead coming from the GND output terminal of the power supply disconnected. You will use this lead as a switch to connect and disconnect the DC voltage from the choke. This circuit demonstrates the effect of DC on an inductor. The neon lamp provides a visual indication of this effect.

3. Turn the + voltage control on the Trainer's power supply to approximately 7.5 volts.

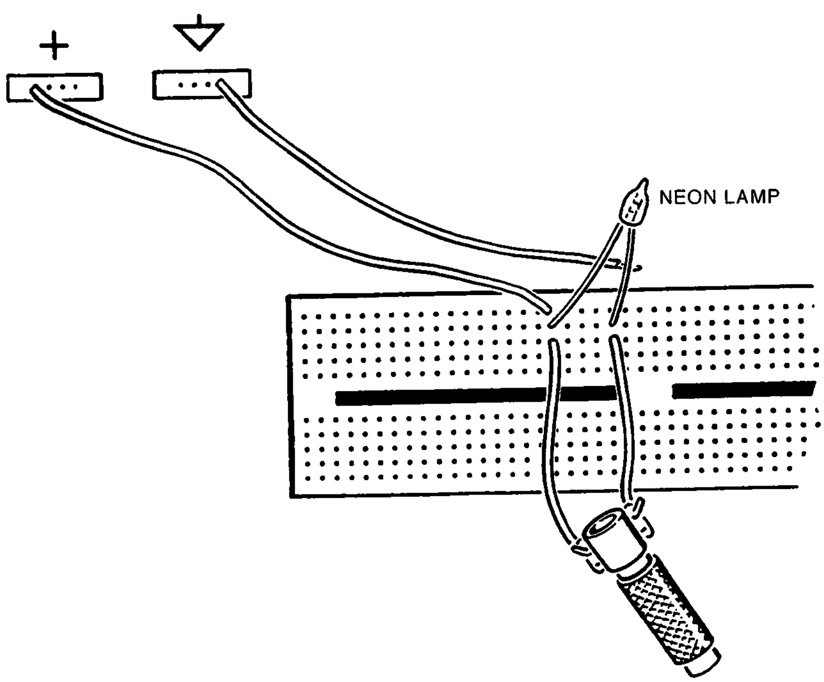


Figure 4-25

4. Connect the GND lead from the power supply to the lead of the neon lamp, or plug the wire into the breadboard socket. Note the effect this has on the neon lamp. (Do not leave this circuit connected for extended periods of time. The relatively high current through the inductor causes it to heat up when you leave it connected to the power supply.)

   Does the neon bulb light? ___________

5. Disconnect the GND power supply lead from the neon lamp. Again note the effect on the lamp.

   Does the lamp light when you remove the lead? ___________

6. Alternately connect and disconnect the GND lead to repeat this procedure. Note the effect on the lamp when the voltage is applied and when it is disconnected.

> Note: It takes approximately 67 volts to cause the neon lamp to light. Based upon this fact, how do you account for the result you noted in the previous steps with the power supply voltage you used? _______
> ____.

6. Adjust the power supply output voltage to 15 volts. Then repeat steps 3 and 4 while you note the effect on the neon lamp as you connect and disconnect the voltage from the circuit.

Discussion

When you apply the DC voltage to the variable inductor, a current begins to flow as indicated in Figure 4-26A. As you know, when current flows through an inductor, it creates a magnetic field. This magnetic field expands outward from the inductor until the current becomes maximum through the circuit. While the magnetic field expands, it induces a counter emf in the inductor.

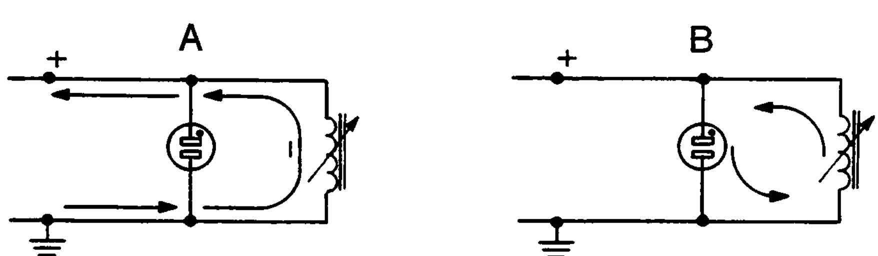


Figure 4-26

Current does not flow through the neon lamp at this time because the applied voltage is not great enough to operate the lamp. Remember, this lamp requires an operating voltage of 67 volts.

When you remove the ground to disconnect the circuit from the power supply, the lamp lights momentarily. This occurs because the magnetic field around the conductor collapses very rapidly. This rapid collapse of the field induces a high voltage in the inductor. Since this voltage is applied to the neon lamp, it causes current to flow through the lamp momentarily. This is shown in Figure 4-26B.

Now, when you increase the voltage and reconnect the circuit, an even greater magnetic field expands around the inductor. When you disconnect the circuit, you again cause induced current to flow through the lamp; but this time the current is greater because the magnetic field collapses more. This results in a brighter blink of the light.

This experiment demonstrates graphically that a voltage is induced in a conductor by relative movement of a magnetic field across an inductor. In addition, it shows that current continues to flow in an inductive circuit for a short time after you remove the applied voltage from the circuit.

Procedure (continued)

7. Construct the circuit as shown in Figure 4-27A. Here, you connect two 1 k ohm resistors in series with the variable inductor. Connect this series RL combination to the GENERATOR section on the Trainer. The actual wiring for this circuit is shown in Figure 4-28A on the next page. You will use this circuit to demonstrate a method to measure the inductance of the circuit.

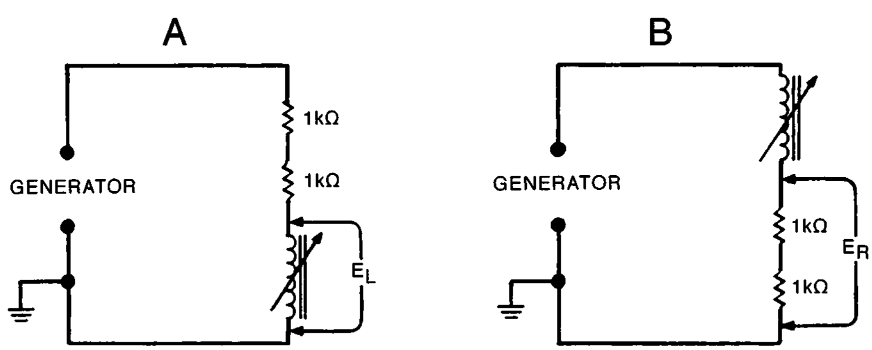


Figure 4-27

8. Be sure the RANGE switch is in the LOW position.

9. Adjust the FREQ control so the output from the generator is 2000 Hz. You can use the mark that you put on the front panel of the Trainer during Experiment 4 for this adjustment.

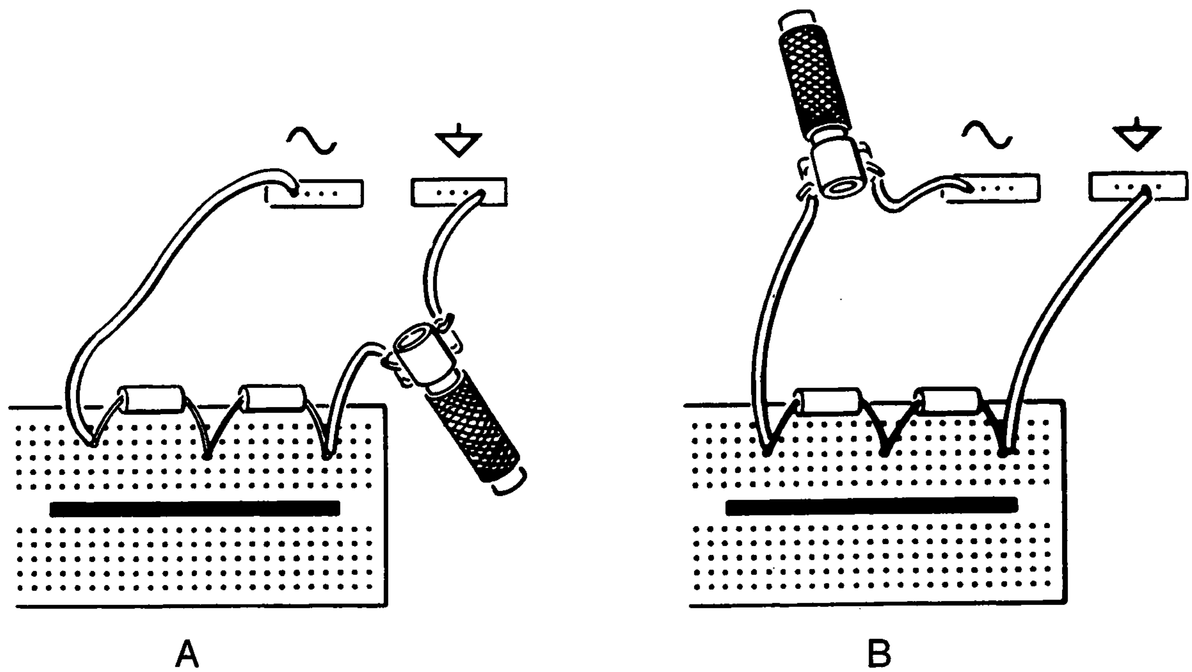


Figure 4-28

10. Turn on your Trainer. Use an AC voltmeter to measure the voltage that is applied to the circuit. This is the voltage between the SINE and GND terminals on the Trainer. Record this value below.

Applied voltage = ___________ volts.

11. Use your AC voltmeter to measure the voltage across the inductor. Record this voltage below:

E_L = ___________ volts

Now, turn off the Trainer and interchange the leads from the generator so that you have the circuit shown in Figure 4-27B. Figure 4-28B shows a pictorial of this circuit.

Turn the Trainer on and measure the voltage drop across the two resistors. Record the resistor voltage below:

E_R = __________ volts

12. Use the voltages that you measured in the previous steps to construct a vector diagram that shows the relationship between these voltages.

13. Use the resistor voltage drop and the resistor value to compute the current flow in the circuit.

I = __________ amperes

14. Use the current and inductive voltage values to compute the inductive reactance of the choke.

X_L = __________ ohms

15. Compute the total circuit impedance and record this value below.

Z = __________ ohms

16. Use the reactance and the frequency of operation to compute the circuit inductance. Record the value of inductance below.

L = __________ henry

17. Compute the circuit phase shift. Record the value of theta (θ) below.

θ = __________ degrees

18. Turn off the power and disconnect the variable indicator from the circuit. Use your Ohmmeter to check the DC resistance of the inductor. Record this value of resistance below.

R_L = __________ ohms

19. Use the value of inductive reactance you computed in step 14 to calculate the Q of the inductor. Record this value below.

Q = __________

Discussion

NOTE: All of the values that are indicated in the following discussion are "typical" values. Your results may vary significantly from those that are presented in the text. There are a number of reasons for this that will be explained.

In this portion of the experiment, you demonstrated a method to determine the inductance of an RL circuit. An inductor with an unknown value is connected in series with a resistor. In this case, the resistor is actually two 1000 ohm resistors in series. This circuit is connected to an AC voltage source.

First, you measured the output voltage from the GENERATOR on the Trainer. Depending upon the Trainer model you use, this can cover a wide range of values. This discussion uses a nominal value of 4.3 volts at 2000 Hz.

Next, you measured the voltage drop across the inductor and resistor in the circuit. Because you used a variable inductor in the experiment, the voltage drop across the inductor can vary depending upon the position of the core. For that reason, this discussion assumes a typical voltage drop of 2 volts. The voltage drop across the resistive portion of the circuit can also vary; however, a typical value is 3.8 volts. The voltage vector diagram for this circuit is shown in Figure 4-29.

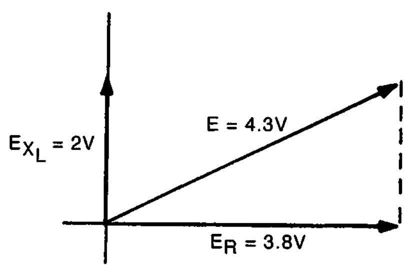


Figure 4-29

You use Ohm's Law to calculate the circuit current:

$$I = \frac{E_R}{R} = \frac{3.8}{2000} = .0019 \text{ A or } 1.9 \text{ mA}$$

Now, you use the circuit current along with the voltage drop across the inductor to determine inductive reactance. The inductive reactance is:

$$X_L = \frac{E_{XL}}{I} = \frac{2}{.0019} = 1052.6 \text{ ohms}$$

You use Ohm's Law to determine the circuit impedance. It is:

$$Z = \frac{E}{I} = \frac{4.3}{.0019} = 2263 \text{ ohms}$$

Since you know that the frequency of the applied voltage is 2000 Hz and the inductive reactance is 1000 ohms, you use a variation of the formula:

$$X_L = 2\pi fL$$

to determine the inductance of the circuit. The inductance is:

$$L = \frac{X_L}{2\pi f} = \frac{1052.6}{12560} = .0838 \text{ H or about } 84 \text{ mH}$$

The rated inductance of the variable inductor can range from 50 mH to 120 mH, depending upon the position of the movable core. However, at lower frequencies, this inductance appears to be lower due to certain electrical characteristics. As you know, an iron core increases the inductance of the coil. The position of this core effects the inductance of the coil. You will learn more about this later in this experiment.

An important point to consider here is that the coil is not a perfect inductor. When you measure the voltage across the inductor, you are actually measuring the voltage drop across the inductive reactance as well as the internal resistance of the coil.

The resistance of the coil itself is in series with the inductive reactance of the coil. If you wanted to, you could draw a vector diagram for the coil because the coil has both a resistive and reactive component.

For the measurement procedure given here, you can consider the resistance of the coil to be negligible if the external resistance value is approximately 10 times greater than the resistance of the coil. The resistance of the variable inductor is about 170 ohms. Since this experiment uses an external resistance of 2000 ohms, the resistance of the coil is neglected in the computations. This resistance, however, combined with the inductive reactance of the coil, gives you a value of inductance that is slightly greater than the actual value of inductance.

In step 19, you determined the Q of the coil. Since the inductance of the coil is variable, the Q will also vary. Given the values you were already presented, however, the Q for the coil is:

$$Q = \frac{X_L}{R} = \frac{1052.6}{170} = 6.19$$

Procedure (continued)

20. Construct the circuit shown in Figure 4-30. Again, the sine wave generator on the Trainer is used as a signal source. You will use this circuit to determine the maximum and minimum values of inductance for the inductor. In addition, you will demonstrate how inductive reactance varies with changes of inductance and frequency.

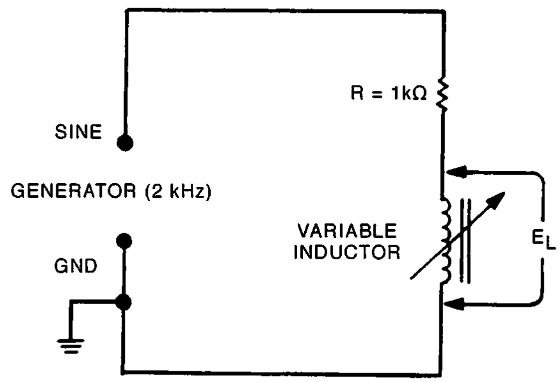


Figure 4-30

21. Make sure that the RANGE switch on the Trainer is set to the LOW position and that the FREQ dial is set to the 2000 Hz position you marked on the front panel. Turn the Trainer on.

22. Connect your voltmeter across the inductor so that you can measure the voltage drop across the inductor. Now, use the plastic hex alignment tool to adjust the variable inductor. Turn the core first in one direction and then in the other. Adjust the core for maximum voltage drop across the inductor and record this voltage below:

$E_{L(max)}$ = __________ volts

23. Next, interchange the leads from the generator so that the circuit configuration appears like the one in Figure 4-31. Measure the voltage across the resistor and record it in the space provided below:

$E_{R(min)}$ = __________ volts

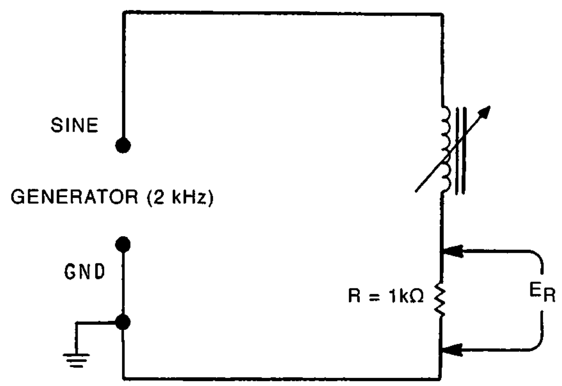


Figure 4-31

24. Use the voltage values measured above and the other circuit values shown in Figure 4-30 to compute the inductance of this coil and record it below.

L = __________ henrys

25. Again, while the voltmeter is connected across the 1000 ohm resistor, adjust the variable inductor for maximum voltage indication on the voltmeter. Record the voltage across the resistor below.

E_R = __________ volts

26. Interchange the leads and measure the voltage across the inductor.

E_L = __________ volts

27. Use these voltage values along with the other known circuit values shown in Figure 4-30 to compute the inductance of the coil and record it below.

L = __________ henrys

28. While your voltmeter is connected across the inductor, use the hex alignment tool to adjust the coil core. Adjust the core to move it down toward the bottom of the coil where the connection terminals are. Observe the voltage as you make the adjustment. Next, adjust the coil in the opposite direction so that the core passes up through the coil and then toward the top near the metal mounting tabs. Observe the voltage with respect to the position of the core. Then complete the following statement. As you move the core out of the coil, the voltage across the coil ______________ .

decreased or increased?

therefore, the inductance has ______________ .

decreased or increased?

29 Move the RANGE switch to the HIGH position and turn it to the 2 kHz position.

30. Again observe the voltage across the coil. Adjust the core in the coil for a maximum voltage across the inductor. Then, observe the resistor voltage while you rotate the generator frequency dial in the clockwise direction to the 20 kHz position. Complete the following statements. As the generator frequency is increases, the voltage across the coil ________________.

decreases or increase?

The increase in frequency causes a/an ________________ in inductive reactance.

decrease or increase?

Discussion

In this part of the experiment, you used the same procedure that was described in the earlier part of this experiment to measure the inductance of the variable inductor. You first adjusted the inductor to its maximum inductance value. To do this you observed the voltage across the inductor and adjusted the inductor for a maximum voltage indication. A maximum voltage means minimum circuit current or maximum opposition to current flow. This means that you adjusted the inductor to its maximum inductance value which gave a maximum inductive reactance and resulted in minimum current flow in the circuit.

Next you measured the resistor and coil voltages. These voltage values depend upon the exact output voltage from the generator in your Trainer. Typical values are 2.6 volts across the resistor and 3.0 volts across the inductor.

You then used the values to calculated the inductance of the circuit. To this, you first used the resistor voltage and the value of resistance to compute the total current flow.

$$I = \frac{E_R}{R} = \frac{2.6}{1000} = .0026 \text{ amperes}$$

Next, you used the value of current you computed above and the inductor voltage to computed the inductive reactance.

$$X_L = \frac{E_L}{I} = \frac{3.0}{.0026} = 1153.8 \text{ ohms}$$

You then computed the inductance since you know the frequency of operation, 2 kHz, and the inductive reactance.

$$L = \frac{X_L}{6.28f} = \frac{1153.8}{6.28\,(2000)} = .0919 \text{ H or } 92 \text{ mH}$$

In step 25, you adjusted the inductor for maximum voltage indication across the resistor. At this point, the inductive reactance is minimum. A typical voltage value for the inductor at this point is 0.8 volts, while the drop across the resistor is 3.2 volts.

You can use these values to calculate circuit current as:

$$I = \frac{E}{R} = \frac{3.2}{1000} = .0032 \text{ A}$$

You can now use this current to calculate the inductive reactance. The formula looks like this:

$$X_L = \frac{E}{I} = \frac{.8}{.0032} = 250 \text{ ohms}$$

Now, you can determine the minimum inductance of the coil as:

$$L = \frac{X_L}{2\pi f} = \frac{250}{6.28\,(2000)} = .0199 \text{ H or } 19.9 \text{ mH}$$

This variation between the rated values of 50 mh to 120 mh and the actual maximum and minimum you calculated is caused by certain electrical characteristics of the inductor. The maximum and minimum rated values for the inductor were calculated at much higher frequencies. At the lower frequencies, such as the 2000 Hz in this experiment, the inductance of the inductor appears to be significantly less. The reason for this phenomena will be explained when you study with resonant circuits. At this time, it is only necessary to realize that this occurs in inductive circuits.

Next, you varied the inductance and the frequency of operation and noted the affect upon the reactance. To do this, you observed the voltage across the coil which is directly proportional to the current in the circuit. The current, of course, is inversely proportional to the reactance.

As you varied the inductance, you should have found that the current increased as the inductance decreased. In the earlier part of the experiment, you adjusted the coil for maximum inductance. This occurred when the core is approximately centered on the coil winding. As you moved the core out of the coil winding in either direction, you should have noted an increase in the voltage across the resistor. This means that the current in the circuit increased due to a decrease in inductance. When you moved the core further out of the coil, you reduced the inductance and the inductive reactance and therefore minimized the opposition to current flow.

Next, you varied the frequency of the applied voltage. You should have found that as you increased the frequency, the voltage across the coil increased. When the frequency increases, the inductive reactance also increases. This increases the total opposition to current flow, thereby decreases the current and the voltage across the resistor.

Procedure (continued)

31. If you have not done so, use the procedure you learned in steps 1 through 13 in Experiment 2 to setup your oscilloscope.

32. Adjust the Trainer Generator section for a sine wave with a frequency of 2 kHz. Use your oscilloscope to observe the sine wave as you adjust the frequency.

33. Switch the Trainer off and construct the circuit shown in Figure 4-32. Note that the probe that is connected between the inductor and resistor in the circuit is attached to the Channel B input of the scope.

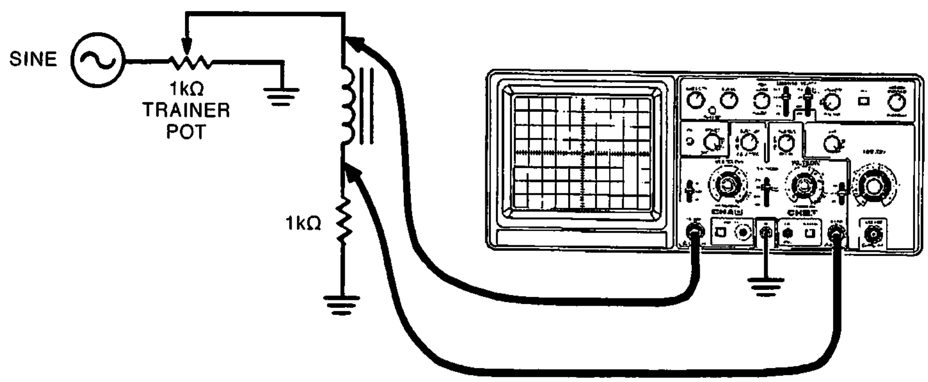


Figure 4-32

34. Select the X-Y mode of operation on your oscilloscope.

    As in Experiment 3, you use the Channel B input in place of the normal scope time base so you can observe Lissajous patterns on the display.

35. Select the highest VOLTS/DIV range position on the scope's vertical input.

36. Center the 1 kilohm pot on the Trainer and switch the Trainer on.

37. Connect your AC voltmeter across the 1 kilohm resistor and adjust the inductor for minimum voltage across the resistor. Disconnect the voltmeter.

38. Use the vertical and horizontal position controls on the scope to center the Lissajous pattern in the display.

39. Adjust the 1 kilohm pot on the Trainer, and the Channel A vertical input VOLTS/DIV range switch and its VARIABLE control on the scope to adjust the size and angle of the pattern until it is 6 cm wide and 6 cm high, as shown in Figure 4-33A.

Make sure the waveform is still centered when you are done adjusting the size and angle of the Lissajous pattern.

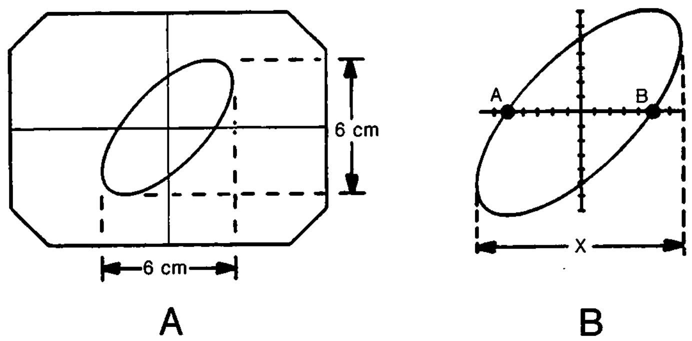


Figure 4-33

40. Count the number of minor divisions for measurement X as shown in Figure 4-33B.

X = __________ divisions

41. Now, count the number of minor divisions between points A and B, as shown in Figure 4-33B.

AB = __________ divisions.

42. Calculate the sine of the phase angle:

$$\text{sine } \theta = \frac{AB}{X}$$

Sine θ = __________

43. Find the phase angle in the table in Appendix C of Unit 3.

Phase angle = __________ degrees

44. With your AC voltmeter, measure the voltage drop across the 1 kilohm resistor.

Resistor voltage = ___________

45. Switch the Trainer off and interchange the positions of the inductor and 1 kilohm resistor in the circuit. Then, switch the Trainer on and use your AC voltmeter to measure the voltage across the inductor.

Inductor voltage = ___________

46. Use the voltage you recorded in steps 44 and 45 to calculate the phase angle of the circuit.

$$\tan\theta = \frac{O}{A} = \frac{E_L}{E_R}$$

Phase angle = ___________ degrees

47. Use the alignment tool to rotate the core of the inductor counterclockwise until it is even with the end of the coil form (tube). This eliminates the core's effect on the coil.

48. With your AC voltmeter, measure the voltage across the inductor.

Inductor voltage = ___________

49. Switch the Trainer off and interchange the positions of the inductor and 1 kilohm resistor in the circuit. Then, switch the Trainer on and use your AC voltmeter to measure the voltage across the resistor.

Resistor voltage = ___________

50. Use the voltages you recorded in steps 48 and 49 to calculate the phase angle of the circuit.

Phase angle = ___________ degrees

51. Readjust your Lissajous pattern until it is again 6 cm high, 6 cm wide, and centered on the display. Count the number of minor divisions for measurement X, and between points A and B, as shown in Figure 4-33B.

X = ___________ divisions
AB = ___________ divisions

52. Use the data in step 51 to calculate the phase angle of the circuit.

Phase angle = __________ degrees

53. Slowly turn the Trainer Generator frequency control counterclockwise until the frequency is approximately 200 Hz. As you reduce the frequency, watch the Lissajous pattern. Pay particular attention to the change in relationship between the X and AB measurement.

54. Readjust your Lissajous pattern until it is again 6 cm high, 6 cm wide, and centered on the display. Count the number of minor divisions for measurement X, and between points A and B, as shown in Figure 4-33B.

X = __________ divisions
AB = __________ divisions

55. Use the data in step 54 to calculate the phase angle of the circuit.

Phase angle = __________ degrees.

56. Switch the Trainer off and remove the circuit components from the Trainer.

Discussion

At the start of this procedure, you adjusted the inductive reactance in the circuit to its maximum value. You then used the Lissajous pattern to calculate the sine of the phase angle. Your pattern should have given you an answer similar to this:

$$\text{sine } \theta = \frac{AB}{X} = \frac{22}{30} = 0.733$$

Refer to Appendix C in Unit 3 and you find the sine of a 47° angle is approximately 0.733.

To verify your answer, you then used the voltage drops across the inductor and the resistor to calculate the phase angle. Your calculations should have given you an answer similar to this:

$$\tan \theta = \frac{O}{A} = \frac{E_L}{E_R} = \frac{3.4 \text{ V}}{2.8 \text{ V}} = 1.21$$

Although your voltage drops may not match those given above, the ratio should be similar. Refer to Appendix C and you find the tangent of 50° is approximately 1.21. As you can see, there is a difference of approximately 3° between the phase

angle you calculated with the Lissajous pattern and the phase angle you calculated with the circuit voltage drops. You should have had similar results. Naturally, the voltage drop calculations should give you a more accurate phase angle than with the Lissajous pattern, however, the Lissajous measurements are suitable for estimating the phase angle.

After you turned the inductor's core to the end of the coil form, the coil's inductance reduced to minimum. Remember, the permeability of air is far less than that of the core. As a result, the inductance reduces when you remove the core from the center of the coil. You discovered this when you calculated the phase angle of the circuit with the voltage drops across the inductor and resistor. For example,

$$\tan \theta = \frac{O}{A} = \frac{E_L}{E_R} = \frac{1.2\text{ V}}{4\text{ V}} = 0.3$$

This gives a phase angle of approximately 17°.

The Lissajous pattern shows the phase angle to be:

$$\text{sine } \theta = \frac{AB}{X} = \frac{8}{30} = 0.267$$

This gives a phase angle of approximately 15°. Again, if you use the Lissajous pattern to estimate phase angle, you will obtain a reasonable approximation.

In the last part of the experiment, you decreased the frequency of the applied signal. As you did this, you should have observed that the X measurement remained relatively constant, while the AB measurement gradually decreased. This happens because the inductive reactance of the coil decreased as the frequency decreased, but the circuit resistance changed only a small amount.

You calculated a phase angle somewhere between 1° and 7°. This depends upon the reactive effect of your scope probes and the accuracy with which you read the Lissajous pattern. As you can see, it becomes increasingly difficult to measure the AB difference when the phase angle approaches 0°.

APPLICATIONS OF INDUCTIVE CIRCUITS

Inductive circuits, like capacitive circuits, are widely used in electronics. The reactive effect of an inductor in an AC circuit makes the inductor valuable in filter and phase shift applications. However, the inductor is less widely used than the capacitor in such applications. The reasons for this is that inductors are larger, heavier, and more expensive. They also come in a narrower range of standard values, and dissipate power. This makes an inductor far less valuable as a reactive component than a capacitor in AC circuits.

The greatest advantage of an inductor in AC applications is that it can produce a reactive effect, while it completes the DC circuit path. The capacitor produces a reactive effect, but blocks DC current. Often, a complete DC current path is required, as well as a reactive effect.

Inductive Filters

You can use series RL networks as simple low- and high-pass filters in the same way that you use series RC circuits. Figure 4-34 shows the two basic types of RL filter circuits. These circuits are resistor-inductor voltage dividers.

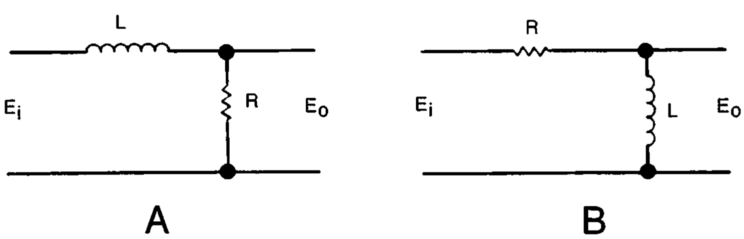


Figure 4-34
Single section RL filters and phase shifter: (A) low-pass filter with lagging phase shift, and (B) high-pass filter with leading phase shift.

The circuit in Figure 4-34A is a low-pass filter. The input signal is applied across the coil and resistor in series, and the output voltage is taken from across the resistor. At low frequencies, the reactance of the coil is low and very little voltage is dropped across it. Most of the voltage is dropped across the output resistor. As the input frequency increases, inductive reactance increases. The inductive reactance becomes larger with respect to the resistance and more of the input voltage is dropped across the coil. Therefore, less voltage appears across the output resistor. As you can see, increasing the frequency causes an increase in the inductive reactance and a corresponding decrease in the output voltage. Low frequencies pass with little or no attenuation while high frequencies are greatly reduced in amplitude by the inductor's reactance.

The circuit in Figure 4-34B is a high-pass filter. Again, the circuit is a voltage divider with the input AC voltage applied across the coil and resistor in series. The output voltage is taken across the inductor. At very high frequencies, the inductive reactance is very high compared to the resistance. Most of the input voltage is developed across the coil for the output terminals. As the input frequency decreases, the inductive reactance decreases. Less voltage is dropped across the coil and more across the resistor. The lower the frequency, the lower the inductive reactance and the lower the output voltage. High frequencies pass with little or no attenuation. Low frequencies are greatly attenuated due to the voltage divider effect.

These simple low-pass and high-pass RL filter circuits produce the same result as equivalent RC circuits. However, they are less desirable because the inductors are larger and more expensive than capacitors. RC circuits are preferred for filter networks when DC current paths are not required.

You can use the following expression to calculate the cut-off frequency, F_{CO}, of the RL filter network shown in Figure 4-34:

$$f_{co} = \frac{R}{2\pi L} = \frac{R}{6.28\ L}$$

The cut-off frequency is the frequency that is above or below those frequencies that the network passes or attenuates. In the expression above, R is in ohms, L is in henrys and F is in Hz. At the cut-off frequency, X_L equals R and the phase shift is 45°. At the cut-off frequency, the output voltage, E_O, is approximately 70% (.707) of the input voltage, E_{IN}, or $E_O = 707\ E_{IN}$. For example, when the input voltage is 8 volts, the output voltage, at the cut-off frequency, is 8 V × .707 = 5.656 volts.

Inductive Phase Shifters

Because an inductor causes the current in a circuit to lag the applied voltage, you can use inductive circuits for phase shifting. The simple series RL circuits shown in Figure 4-34 can also serve as phase shifters. With these circuits, you can obtain a phase shift between 0° and 90°. In the circuit shown in Figure 4-34A, the output voltage lags the input voltage. The inductive reactance and the resistance values determine the phase angle.

The circuit of Figure 4-34B produces a leading phase shift. The output leads the input by a phase angle between 0° and 90°. As the amount of phase shift produced by the circuit approaches 90°, the output voltage becomes greatly attenuated. Theoretically, with a 90° phase shift the output is zero. For that reason,

simple RL phase shift circuits provide phase shifts of approximately 60° or less. The greater the phase shift, the greater the need for amplification in the circuit, to restore the amplitude of the output signal.

The amount of phase shift that is produced by these circuits is a function of the inductance, the resistance, and the input frequency. The following formulas calculate tangent of the phase shift:

$$\tan\theta = \frac{X_L}{R} \text{ (Figure 4-34A)}$$

$$\tan\theta = \frac{R}{X_L} \text{ (Figure 4-34B)}$$

These formulas assume that the resistance of the inductor is negligible when as compared to the resistor's value.

To obtain phase shifts greater than 90°, the simple RL networks in Figure 4-34 are cascaded. While you can obtain large values of phase shift, the attenuation of the cascaded circuit is considerable. Some type of amplification is generally required to offset the loss in the circuit. Later in your studies, you will study the transistor amplifier combined with the RL network.

As with RL filters, RL phase shifters are less desirable than RC phase shifters. Inductors are larger, more expensive, and have greater losses than capacitors. RC networks are preferred when DC current paths are not required.

Programmed Review

103. RL circuits are widely used in __________ and __________ __________ applications.

104. (filtering, phase shifting) It is the reactive effect of an inductor that permits such applications. For a given inductance, the reactance changes when the __________ changes.

105. (frequency) Another component whose reactance changes with frequency is the __________ .

106. (capacitor) When a reactive component such as an inductor or capacitor is combined with a resistor in series, the RL or RC combination can provide filtering or phase shifting. The series RL combination forms a __________ __________ circuit.

107. (voltage divider) The input voltage is applied across the series combination while the output can be taken from across either the resistor or inductor depending upon the application. When you use the RL circuit in frequency selective applications it is called a __________ .

108. (filter) If the output of a series RL circuit is taken from across the resistor, the circuit is a __________ __________ filter.

109. (low-pass) At the higher frequencies, X_L increases and less voltage appears across the output __________ .

110. (resistor) The circuit thereby attenuates __________ frequencies and lets __________ frequencies pass.

111. (high, low) To use the series RL circuit as a high-pass filter, the output is taken from across the __________ .

112. (inductor) A high-pass filter attenuates the ___________ frequencies but lets the ___________ frequencies pass.

113. (low, high) One frequency designates the dividing line between frequencies that are passed or attenuated. This is called the ___________ ___________ frequency.

114. (cut-off) The values of ___________ and ___________ in the circuit determine the cut-off frequency.

115. (resistance, inductance) You compute the cut-off frequency for both high- and low-pass filters with the formula ___________.

116. ($f_{co} = \frac{R}{6.28\,L}$) If R = 140 ohms and L = 107 mH, the cut-off frequency is ___________ Hz.

117. (208.3 $\quad f_{co} = \frac{R}{6.28\,L} = \frac{140}{6.28\,(.107)} = 208.3$ Hz) You can also use the series RL network for phase shifting. If the output is taken from across the resistor it will ___________ the input.

118. (lag) The current lags the applied voltage in an RL circuit. Therefore, the resistor (output) voltage, which is in phase with the current, lags the input or applied voltage. To achieve an output that leads the input, you take the voltage from across the ___________.

119. (inductor) The maximum possible phase shift of a series RL circuit is ___________.

120. (90°) At 90° the output is zero. Therefore practical values of phase shift are less than 90°. The exact phase shift is a function of the ___________ and ___________ ___________.

121. (resistance, inductive reactance) To obtain phase shift values greater than 90°, you can ___________ RL circuits.
122. (cascade) RL networks are large, heavy, and expensive due to the ___________.
123. (inductor) As a result, ___________ networks are usually preferred over RL networks.
124. (RC)

UNIT EXAMINATION

The following multiple choice examination is designed to test your understanding of the material that was presented in this unit. Place a check beside the multiple choice answer (A, B, C, or D) that you feel is most correct. After you complete the examination, compare your answers with the correct ones that appear after the exam.

1. Inductance is the property of an electrical circuit that opposes changes in:

   A. current.
   B. applied voltage.
   C. induced voltage.
   D. magnetic field.

2. The unit of inductance is the:

   A. ohm.
   B. reactance.
   C. farad.
   D. henry.

3. Which of the following factors does not cause the inductance of a coil to increase.

   A. increasing number of turns of wire
   B. increasing coil length
   C. increasing the diameter
   D. adding an iron core

4. Three inductors, L1 = 50 mH, L2 = 175000 μH and L3 = .4 H, are connected in series with no mutual inductance. The total inductance is:

   A. 22.5 mH.
   B. 175.45 mH.
   C. 625 mH.
   D. 1800 mH.

5. A series RL circuit contains a variable inductor with an iron core. When you remove the iron core, the voltage drop across the resistor:

   A. increases.
   B. decreases.
   C. remains the same.

6. The unit of inductive reactance is:

   A. henry.
   B. ohm.
   C. Hz.
   D. millihenry.

7. The total opposition to current flow in a series RL circuit is called:

   A. R.
   B. X_L.
   C. Z.
   D. H.

8. Inductive reactance is a function of:

   A. E.
   B. I.
   C. f.
   D. θ.

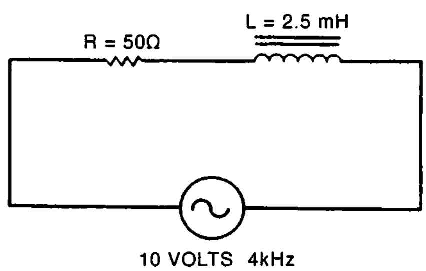


Figure 4-35
Circuit for exam questions 9 through 14.

9. Refer to Figure 4-35. The impedance of the circuit is approximately:

   A. 50 ohms.
   B. 63 ohms.
   C. 80 ohms.
   D. 112 ohms.

10. The voltage across the resistor in Figure 4-35 is approximately:

    A. 3.7 volts.
    B. 6.3 volts.
    C. 8.2 volts.
    D. 10 volts.

11. The phase shift in the circuit of Figure 4-35 is approximately:

    A. 51° lagging.
    B. 62° leading.
    C. 81° leading.
    D. 90° lagging.

12. The power that is dissipated in the circuit of Figure 4-35 is approximately:

    A. 175 mW.
    B. 420 mW.
    C. 635 mW.
    D. 780 mW.

13. The cut-off frequency in the circuit of Figure 4-35 is approximately:

    A. 1800 Hz.
    B. 2.5 kHz.
    C. 3185 Hz.
    D. 4.39 kHz.

14. The Q of the circuit in Figure 4-35 is approximately:

    A. .79
    B. 1.26
    C. 1.6
    D. 12.6

15. An RL voltage divider with the output voltage taken from across the resistor is called a:

    A. low-pass filter.
    B. high-pass filter.
    C. leading phase shifter.
    D. inductive voltage divider.

EXAMINATION ANSWERS

1. A — current.

2. D — henry.

3. B — increasing coil length. Increasing coil length decreases the inductance.

4. C — 625 mH L1 = 50 mH, L2 = 175000 μH = 175 mH, L3 = .4 H = 400 mH. $L_T = L1 + L2 + L3 = 50 + 175 + 400 = 625$ mH

5. A — increases. When you remove the iron core, this decreases the inductance and the inductive reactance, therefore the opposition to current flow decreases. As a result, the current and the resistor voltage drop increase.

6. B — ohms.

7. C — Z impedance.

8. C — f. Inductive reactance is a function of frequency.

9. C — 80 ohms L = 2.5 mH = .0025 H f = 4 kHz = 4000 Hz $X_L = 6.28\ fL = 6.28\ (4000)\ (.0025)$ $X_L = 62.8$ ohms or approximately 63 ohms.

$$Z = \sqrt{R^2 + X_L{}^2} = \sqrt{50^2 + 63^2} = \sqrt{2500 + 3969}$$

$$Z = \sqrt{6469} = 80.4 \text{ or approximately 80 ohms}$$

10. B — 6.3 volts. $I = \frac{E}{Z} = \frac{10}{80} = .125$ amperes
    $E_R = IR = .125\ (50) = 6.25$ volts or approximately 6.3 volts

11. A — 51° lagging. $\theta = \frac{X_L}{R} = \frac{63}{50}$
    $\tan\theta = 1.26$ $\theta = 51.56°$, approximately 51° or 52°

12. D — 780 mW. $P = I^2R = (.125)^2\ 50 = .78125$ W or approximately 780 mW (milliwatt)

13. C —3185 Hz. $f_{co} = \frac{R}{6.28\ L} = \frac{50}{6.28\ (.0025)} = 3184.7$ Hz

14. B —1.26 $Q = \frac{X_L}{R} = \frac{63}{50} = 1.26$

15. A —low-pass filter.

UNIT 5

TUNED CIRCUITS

CONTENTS

INTRODUCTION

Tuned circuits are used extensively in electronics. They are used to determine the frequency at which oscillators and amplifiers operate, to separate wanted signals from unwanted signals, and to eliminate interference and noise. Without tuned circuits, many phases of electronics could not exist.

Mush of the math in this unit is derived from the equations that are in Units 3 and 4. In addition, a great deal of the background theory that is necessary to understand Unit 5 is also in the two preceding units. Be sure than you thoroughly understand the concepts that were presented in Unit 3 and Unit 4 before you begin Unit 5.

One final point. After you complete your study of parallel resonance, you may wish to review Appendix B. There, you will find another "tool" that you may find useful when you study RLC circuits. It is called the "j operator." The appendix provides an explanation of the purpose of the j operator and how it can be used to determine phase and magnitude relationships.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define resonance, resonant frequency, half-power point, flywheel effect, tank circuit, self-resonance, band-pass filter, and band-stop filter.

2. Calculate the impedance, current, voltage, power factor, and phase angle for series and parallel RLC circuits..

3. Determine the capacitor rating, in kilovars, necessary to correct an inductive circuit for a unity power factor.

4. State six characteristics of a series-resonant RLC circuit..

5. State six characteristics of a parallel-resonant RLC circuit.

6. Determine the Q of a series or parallel circuit at resonant frequency.

7. Calculate the power savings, in kilowatt hours, of a circuit that has been corrected to a unity power factor.

8. From the schematic diagram, identify the six basic types of filters.

9. Name the type of filter that produces a particular response curve.

10. Calculate the resonant frequency of a circuit.

1. Determine the bandwidth of a series- or parallel-resonant circuit.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "RLC Circuits."	________
☐ Complete Programmed Review Frames 1-26.	________
☐ Read "Resonance."	________
☐ Complete Programmed Review Frames 27-34.	________
☐ Read "Series Resonance."	________
☐ Complete Programmed Review Frames 35-50.	________
☐ Read "Q and bandwidth in series-resonant circuit."	________
☐ Complete Programmed Review frames 51-60.	________
☐ Perform Experiment 7: Series Resonance.	________
☐ Read "Parallel Resonance."	________
☐ Complete Programmed Review Frames 61-77.	________
☐ Perform Experiment 8: Parallel Resonance.	________
☐ Read "LC Circuits."	________
☐ Complete Programmed Review Frames 78-89.	________
☐ Perform Experiment 9: LC Filters.	________
☐ Study the Summary.	________
☐ Complete the Unit Examination.	________
☐ Check the Examination Answers.	________

RLC CIRCUITS

RLC circuits are circuits which have resistors, inductors, and capacitors that have been connected together in some manner. The simplest RLC circuit consists of a resistor, an inductor, and a capacitor which are connected in series. This is called a series RLC circuit.

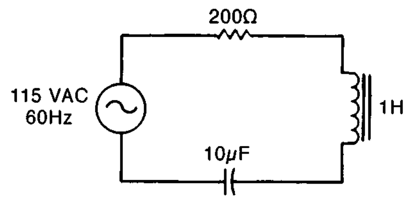


Figure 5-1
Series RLC circuit.

Series RLC Circuits

Figure 5-1 shows a resistor, coil, and capacitor which are connected in series with an AC generator. Because the values of capacitance, inductance, and frequency are given, you can compute the reactances in the circuit with the following formulas:

$$X_L = 2\pi fL \quad \text{and} \quad X_C = \frac{1}{2\pi fC}$$

The inductive reactance is:

$$X_L = 2\pi fL$$
$$X_L = 6.28 \times 60\text{ Hz} \times 1\text{ H}$$
$$X_L = 377\ \Omega$$

The capacitive reactance is:

$$X_C \frac{1}{2\pi fC}$$

$$X_C \frac{1}{6.28 \times 60\text{ Hz} \times 0.00001\text{ fd}}$$

$$X_C \frac{1}{0.00377}$$

$$X_C = 265\ \Omega$$

The reactance values combine with the resistance value to form an impedance to current flow. Recall that there is a general formula for impedance: $Z = \sqrt{R^2 + X^2}$. When the reactance is caused by capacitance, the formula becomes: $Z = \sqrt{R^2 + X_C^2}$. When inductive reactance is involved, the formula becomes $Z = \sqrt{R^2 + X_L^2}$.

The circuit shown in Figure 5-1 contains both capacitive and inductive reactance. Therefore, you need a formula which contains both X_C and X_L. A vector diagram of the reactances and resistance in the circuit will help you develop such an equation. Figure 5-2 shows the vector diagram for this circuit. When you follow the conventions established earlier, R is plotted at 0; X_L is plotted at +90°, and X_C is plotted at –90°. Notice that this places X_L 180° out of phase with X_C. For this reason, X_L and X_C tend to cancel. However, because X_L is greater than X_C, the resultant reactance is inductive in nature.

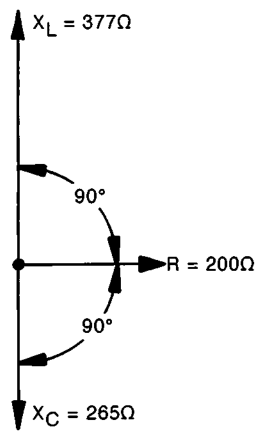


Figure 5-2
Vector diagram for a series RLC circuit.

Figure 5-3 shows the resultant vector. Because X_L is 377 Ω and X_C is 265 Ω, X_L can completely cancel X_C and still have a value of 112 Ω. That is, 377 Ω – 265 Ω = 112 Ω. Thus, when a circuit has both capacitive reactance and inductive reactance, the net reactance is the difference between the two.

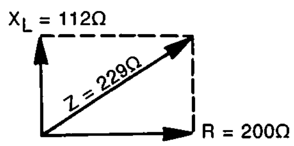


Figure 5-3
Resultant vector after X_L cancels X_C.

Because of this, the complete formula for the impedance in a series RLC circuit is:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{200^2 + (377 - 265)^2}$$

$$Z = \sqrt{200^2 + (112)^2}$$

$$Z = \sqrt{40{,}000 + 12{,}544} \sim/(200)2 + (112)2$$

$$Z = \sqrt{52{,}544}$$

$$Z = 229\ \Omega$$

The net result is the same as if a coil that has an X_L of 112 Ω is connected in series with a resistance of 200 Ω. Figure 5-3 shows the final vector diagram.

You use the formula above for impedance when X_L is greater than X_C. Obviously, there will be cases in which X_C is larger than X_L. Such a case is shown in Figure 5-4A. Here X_L is 10 ohms; X_C is 40 ohms and R is 40 ohms.

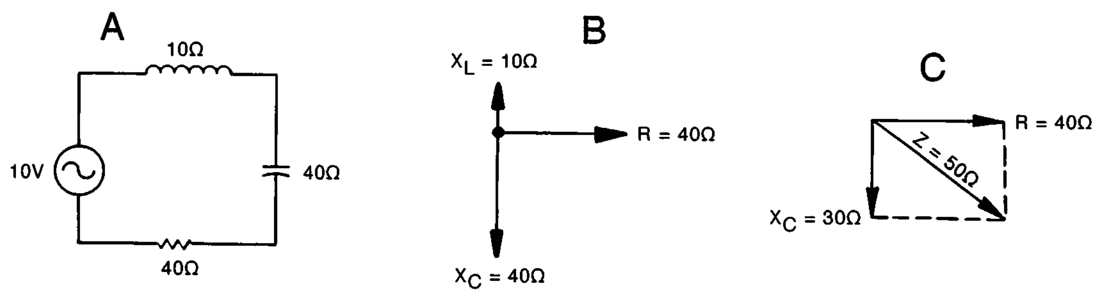


Figure 5-4
Circuit and vectors in which X_C is greater than X_L.

Figure 5-4B shows the vector diagram for this circuit. Note that in this case X_C more than cancels X_L. Thus, to find the net reactance you subtracting X_L from X_C. As shown in Figure 5-4C, the result is a capacitive reactance of 30 Ω. Consequently, when X_C is larger than X_L, the formula for impedance becomes:

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

Using this formula, we find that the total impedance of this circuit is:

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

$$Z = \sqrt{(40)^2 + (40 - 10)^2}$$

$$Z = \sqrt{(40)^2 + (30)^2}$$

$$Z = \sqrt{1600 + 900}$$

$$Z = \sqrt{2500}$$

$$Z = 50\ \Omega$$

Once you know the impedance of the circuit, you can determine other circuit values. When you use formulas that were developed in earlier units, you can compute values such as current, the voltage dropped by each component, and the power factor. For example, the current in Figure 5-4A must be:

$$I = \frac{E}{Z} = \frac{10\ V}{50\ \Omega} = 0.2 \text{ amps}$$

This allows you to find the voltage drop across each component:

$$E_R = I\,(R) = 0.2A \times 40\ \Omega = 8\ V$$

$$E_L = I\,(X_L) = 0.2A \times 10\ \Omega = 2\ V$$

$$E_C = I\,(X_C) = 0.2A \times 40\ \Omega = 8V$$

You can determine the power factor with the formula:

$$PF = \frac{R}{Z} = \frac{40\ \Omega}{50\ \Omega} = 0.80$$

And since the power factor is also equal to the cosine of the angle, you can find the angle from a cosine chart. This chart indicates that the angle is about 36.5°. The vector shown in Figure 5-4C shows that this is a negative angle. This means that the circuit acts capacitively.

To compute apparent power in volt-amps, multiply the applied voltage times the current: $VA = E \times I = 10\ V \times 0.2A = 2\ VA$. However, the true power is somewhat less since only the resistor can dissipate power:

$$P = I^2R = (0.2A)^2 \times 40\ \Omega = 0.04 \times 40 = 1.6\ W$$

The above procedure is a step-by-step way to analyze a series RLC circuit. With this procedure, you can compute all of the important circuit values from a few given values.

Parallel RLC Circuits

Figure 5-5 shows a parallel RLC circuit. Because the three components are in parallel, the same voltage is applied across each. As you learned earlier, it is generally easier to work with currents in problems of this type. Recall that when a reactance is in parallel with a resistance, the total current is the vector sum of the two branch currents. That is,

$$I_T = \sqrt{I_R^2 + I_X^2}$$

In this formula, I_X may be the current through either a capacitor or an inductor.

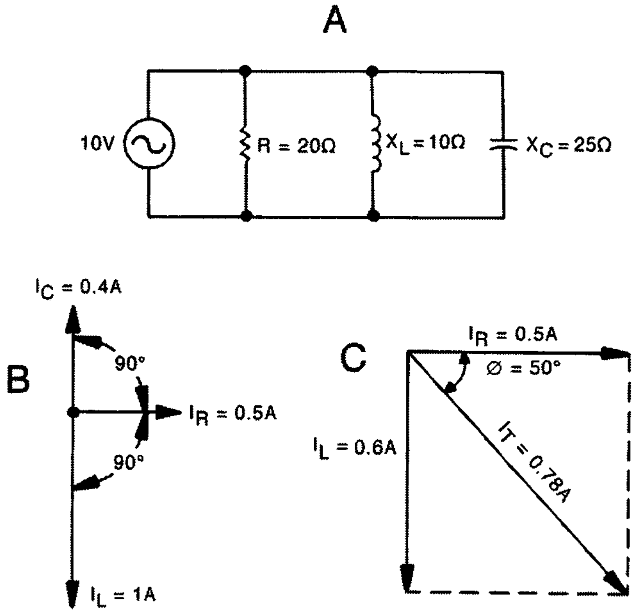


Figure 5-5
Parallel RLC circuit.

You can expand this formula to handle situations like that shown in Figure 5-5A where both inductors and capacitors are used. The first step is to find the current through each branch. This is easy to do since all of the pertinent values are given. The branch currents are:

$$I_R = \frac{E}{R} = \frac{10\text{ V}}{20\ \Omega} = 0.5\text{ amperes}$$

$$I_L = \frac{E}{X_L} = \frac{10\text{ V}}{10\ \Omega} = 1\text{ ampere}$$

$$I_C = \frac{E}{X_C} = \frac{10\text{ V}}{25\ \Omega} = 0.4\text{ amperes}$$

Figure 5-5B shows the branch currents plotted as vectors. I_R is in phase with the applied voltage and is plotted at 0°. I_L lags the applied voltage by 90° while I_C leads the applied voltage by 90°. Notice that I_C is 180° out of phase with I_L. As far as the source current is concerned, these two currents tend to cancel. I_L is larger than I_C. Thus, the total current through the two reactive components is I_L minus I_C or 1 ampere minus 0.4 amperes equals 0.6 amperes. Because the reactive currents subtract, the formula for the total current is:

$$I_T = \sqrt{I_R{}^2 + (I_L - I_C)^2}$$

Now, use this formula and solve for the total current in Figure 5-5A:

$$I_T = \sqrt{I_R{}^2 + (I_L - I_C)^2}$$

$$I_T = \sqrt{0.5^2 + (1 - 0.4)^2}$$

$$I_T = \sqrt{0.5^2 + (0.6)^2}$$

$$I_T = \sqrt{0.25 + 0.36}$$

$$I_T = \sqrt{0.61}$$

$$I_T = 0.78\text{A}$$

This is further illustrated by the vector shown in Figure 5-5C. The total current is shown as the vector sum of I_R and I_L. Of course, the value of I_L is the resultant current after you subtract the value of I_C from the original value of I_L.

Once you know the total current in the circuit, you can compute other values. For example, the impedance of the circuit is:

$$Z = \frac{E}{I_T} = \frac{10\text{ V}}{0.78\text{ A}} = 12.8\ \Omega$$

This is the impedance of the three components in parallel.

Also, you can find the phase angle with the formula:

$$\tan\theta = \frac{I_X}{I_R} = \frac{0.6}{0.5} = 1.2$$

When you look this number up in Appendix C at the end of Unit 3, you find that a tangent of 1.2 corresponds to an angle of about 50°. However, as shown in Figure 5-5C, θ is a negative angle because the circuit acts inductive. Consequently, the total current lags the applied voltage by about 50°.

Programmed Review

1. When a coil and a resistor are connected in series, the formula to find the total impedance is $Z = \sqrt{R^2 + X_L{}^2}$. By the same token the formula to find the impedance of a capacitor and resistor in series is ________________.

2. ($Z = \sqrt{R^2 + X_C{}^2}$) When a capacitor, a coil, and a resistor are connected in series, you must expand the formula to include both X_L and X_C. If X_L is larger, the proper formula is:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

However, when X_C is larger than X_L the proper formula is ____________.

3. ($Z = \sqrt{R^2 + (X_C - X_L)^2}$) A series RLC circuit has an inductor with an X_L of 25 ohms, a capacitor with an X_C of 10 ohms, and a resistance of 15 ohms. The total impedance is ___________ ohms.

4. (21.2) If the applied voltage is 10.6 volts, the current in the circuit is ___________ amperes.

5. (0.5) The voltage drop across the resistor is ___________ volts.

6. (7.5) The voltage drop across the coil is ___________ volts.

7. (12.5) The voltage drop across the capacitor is ___________ volts.

8. (5) The apparent power in the circuit is ___________ volt-amps.

9. (5.3) The true power is ___________ watts.

10. (3.75) The power factor of the circuit is ___________.

11.	(0.707) The current is ________° out of phase with the applied voltage.
12.	(45) Because the circuit acts inductively, the voltage ________ the current.
13.	(leads) In parallel AC circuits, it is easier to work with currents. When a coil and a resistor are connected in parallel, you can find the total current with the formula: $I_T =$ ________.
14.	($I_T = \sqrt{I_R^2 + I_L^2}$) When a capacitor and a resistor are connected in parallel, the equation becomes $I_T =$ ________.
15.	($I_T = \sqrt{I_R^2 + I_C^2}$) If a capacitor, a coil, and a resistor are connected in parallel, the formula must be expanded to include I_L and I_C. If I_L is larger than I_C, the proper formula is $I_T =$ ________.
16.	($I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$) On the other hand, if I_C is larger than I_L, the formula is: $I_T =$ ________.
17.	($I_T = \sqrt{I_R^2 + (I_C - I_L)^2}$) A coil with an X_L of 10 ohms, a 20 ohm resistor, and a capacitor with an X_C of 30 ohms are connected in parallel across a 60-volt AC power supply. The current through the coil is: $I_L =$ ________ amperes.
18.	(6) The current through the resistor is: $I_R =$ ________ amperes.
19.	(3) The current through the capacitor is: $I_C =$ ________ amperes.
20.	(2) The total current (I_T) in the circuit is ________ amperes.
21.	(5) The total impedance of the circuit is ________ ohms.

22.	(12) The apparent power in the circuit is ____________ volt-amps.
23.	(300) The true power is ____________ watts.
24.	(180) The phase angle is the angle whose tangent equals I_X/I_R. In this example, $\tan \theta$ = ____________ .
25.	(4/3 or 1.333) From the tangent table, you find that this corresponds to an angle of about ____________°.
26.	(53) Since the circuit acts inductive the current lags the voltage and the angle is negative.

RESONANCE

In earlier units you studied the inductive reactance of coils and the capacitive reactance of capacitors. Figure 5-6A shows a coil and a capacitor connected in parallel. If a voltage is applied between terminals A and B, the operation of this circuit depends upon the frequency of the applied voltage. If the voltage is DC, the capacitor acts like an open while the inductor acts like a short. That is, the X_C is infinite while the X_L is 0.

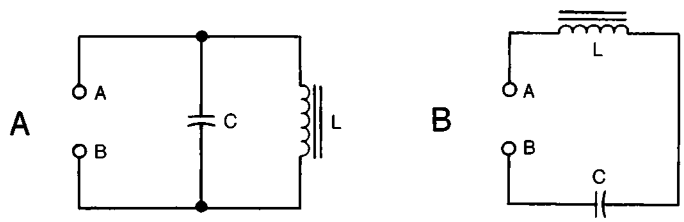


Figure 5-6
LC circuits.

Now assume that the applied voltage is not DC but is a very low frequency AC instead. In this case, the X_L is very low and the X_C is quite high. The exact values depend upon the values of C, L, and the applied frequency.

If you gradually increase the frequency, the X_L will gradually increase while the X_C will gradually decrease. As you increase the frequency further, you will eventually reach a point at which the value of X_L is the same as the value of X_C. That is, for any combination of L and C, there is some frequency at which X_L equals X_C. This is true whether the two components are connected in parallel as shown in Figure 5-6A or in series as shown in Figure 5-6B. The condition at which X_L equals X_C is called resonance. Also, the frequency at which X_L equals X_C is called the resonant frequency and is abbreviated f_O.

Recall that the formula for X_L is:

$$X_L = 2\pi fL$$

And, the formula for X_C is:

$$X_C = \frac{1}{2\pi fC}$$

With these two formulas, you can derive an equation for the resonant frequency, f_O. By definition, at resonance, $X_L = X_C$. Therefore:

$$2\pi fL = \frac{1}{2\pi fC}$$

To solve for the frequency at which L and C are resonant, you can rearrange this formula. To do this, you first multiply both sides of the equation by $2\pi fC$. This gives you:

$$2\pi\, fL\, (2\pi\, fC) = \frac{1\, (\cancel{2\pi fC})}{\cancel{2\pi fC}}$$

or:

$$2\pi\, fL\, (2\pi\, fC) = 1$$

Simplifying this, you find that:

$$4\pi^2 f^2 LC = 1$$

When you divide both sides by $4\pi^2LC$ you get:

$$f^2 = \frac{1}{4\pi^2 LC}$$

Now, take the square root of both sides:

$$\sqrt{f^2} = \sqrt{\frac{1}{4\pi^2 LC}}$$

Of course, $\sqrt{f^2} = f$ and you can write $\sqrt{\frac{1}{4\pi^2 LC}}$ as $\frac{\sqrt{1}}{\sqrt{4\pi^2 LC}}$

Thus the equation becomes:

$$f = \frac{\sqrt{1}}{\sqrt{4\pi^2 LC}}$$

The square root of 1 is 1 and the square root of $4\pi^2$ is 2π. Thus, the final equation is:

$$f_O = \frac{1}{2\pi\sqrt{LC}}$$

Or, when you divide 2π into 1:

$$f_O = \frac{0.159}{\sqrt{LC}}$$

You can apply this formula to any LC circuit to find the frequency at which it is resonant. For example, assume that a 100 mH coil is connected in series with a .022 μF capacitor. What is the resonant frequency?

$$L = 0.1\ \text{H}$$

$$C = .000\ 000\ 022\ \mu\text{F}$$

$$f_o = \frac{0.159}{\sqrt{LC}}$$

$$f_o = \frac{0.159}{\sqrt{0.1\ \text{H} \times 0.000\ 000\ 022\ \mu\text{F}}}$$

$$f_o = \frac{0.159}{\sqrt{0.000\ 000\ 0022}}$$

$$f_o = \frac{0.159}{\sqrt{0.000047}}$$

$$f_o = 3383\ \text{Hz or } 3.383\ \text{kHz}$$

Now try another example. A 5 μF capacitor is in parallel with a 50 μH coil. What is the resonant frequency?

$$L = 0.000\ 05\ \text{H}$$

$$C = 0.000\ 005\ \mu\text{F}$$

$$f_o = \frac{0.159}{\sqrt{0.000\ 05\ \text{H} \times 0.000\ 005\ \mu\text{F}}}$$

$$f_o = \frac{0.159}{\sqrt{0.000\ 000\ 000\ 25}}$$

$$f_o = \frac{0.159}{\sqrt{0.0000159}}$$

$$f_o = 10{,}000\ \text{Hz or } 10\ \text{kHz}$$

If you rearrange the resonance formula in a different way, you can derive two more important equations. First you can derive an equation to find the value of capacitance that is needed to resonate with a given value of inductance at a given frequency. As before:

$$X_L = X_C$$

$$2\pi\,fL = \frac{1}{2\pi\,fC}$$

$$4\pi^2\,f^{f2}\,LC = 1$$

$$C = \frac{1}{4\pi^2\,f^2\,L}$$

Or, you can rearrange the equation like this:

$$L = \frac{1}{4\pi^2\,f^2\,C}$$

You can use this equation to find the value of inductance that is needed to resonate with a given value of capacitance at a given frequency. Now try to use these two formulas in a couple of practical problems.

What value of capacitor must be connected across a 5 Henry coil in order that the circuit resonate at 60 Hz?

$$L = 5\text{ H}$$

$$f = 60\text{ Hz}$$

$$C = \frac{1}{4\pi^2\,f^2\,L}$$

$$C = \frac{1}{4\,(3.14)^2\,(60)^2\,(5)}$$

$$C = \frac{1}{39.4\,(3600)\,(5)}$$

$$C = \frac{1}{709\,200}$$

$$C = 0.0000014\ \mu F$$

$$C = 1.4\ \mu F$$

What value of coil must be connected in series with a 1 µF capacitor to make the circuit resonate at 5 kHz?

$$C = 0.000\,001\ \mu F$$

$$f_O = 5000\ Hz$$

$$L = \frac{1}{4\pi^2 f^2 C}$$

$$L = \frac{1}{4\,(3.14)^2\,(5000)^2\,(.000\,001)}$$

$$L = \frac{1}{39.4\,(25{,}000{,}000)^2\,(.000\,001)}$$

$$L = \frac{1}{985}$$

$$L = 1.02\ mH$$

These examples show you how to find the resonant frequency, the value of L, or the value of C. You can use these formulas to find any one of these variables, if you know the other two. These formulas work equally well for both series and parallel LC circuits. That is, for given values of L and C, the resonant frequency is the same regardless of how L and C are connected. Nevertheless, as you will see later, a series resonant circuit behaves very differently than a parallel resonant circuit.

Programmed Review

27. For any inductor-capacitor combination, there is some frequency at which X_L equals X_C. This is called the __________ frequency.

28. (resonant) The formula for f_o is: __________ .

29. ($f_o = \frac{1}{2\pi\sqrt{LC}}$ or $f_o = \frac{.159}{\sqrt{LC}}$) You can use either of these formulas to find that a 1 H coil and a 1 μF capacitor have a resonant frequency of __________ Hz.

30. (159 Hz) You can rearrange the resonant formula to find the value of the coil if you know the value of the capacitor and the resonant frequency. The formula for L is: L = __________.

31. ($L = \frac{1}{4\pi^2 f^2 C}$) Use this formula to determine what value of inductor must be connected across a 5 μF capacitor to make the circuit resonate at 100 Hz? L = __________ H.

32. (0.5) Also, you can rearrange the resonant formula so that you can find the value of the capacitor when you know the value of the inductor and the resonant frequency. The formula is: C = __________.

33. ($C = \frac{1}{4\pi^2 f^2 L}$) Use this formula to what value of C you should chose to resonate at 1 kHz with an inductance of 1 H? C = __________ μF.

34. (0.025) Appendix A at the end of this unit shows a graphic way to solve resonance problems. Turn to Appendix A and use the graph to solve the problems in Frames 29, 31, and 33 of this review.

SERIES RESONANCE

The previous section defined resonance and gave a formula to determine the resonant frequency of any LC circuit. In this section you will see that an LC circuit has characteristics at resonance which it does not have at any other frequency. These unusual characteristics make the resonant circuit extremely important.

Figure 5-7 shows a series circuit consisting of a capacitor, an inductor, and a resistor. The values of L and C are not given, nor is the frequency of the applied signal. Nevertheless, you know that the circuit is at the resonant condition because X_L is equal to X_C.

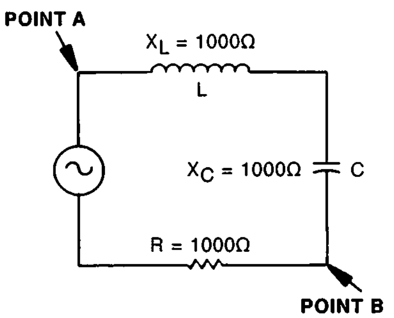


Figure 5-7
At resonance, $X_L = X_C$.

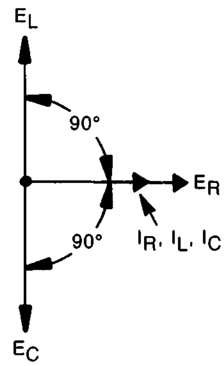


Figure 5-8
Vector diagram of a series resonant circuit.

The applied AC signal forces current to flow through the series circuit. Because the components are in series, the same current flows through all components.

As current flows through the circuit, a voltage is developed across each component. Because $R = X_L = X_C$, the voltages developed across each component are equal. That is, $E_R = E_L = E_C$. However, this is true only of the magnitude of the voltage. The phase of the voltage is different across each component. The voltage across R is in phase with the circuit current. However, the voltage across the coil leads the current by 90°. Also, the voltage across the capacitor lags behind the current by 90°. The best way to visualize these phase relationships is with vector diagrams.

Figure 5-8 shows the vector diagram of the voltages and current. I_R, I_L, I_C, and E_R are all in phase with the applied current. Consequently, these are shown at 0°. E_L is drawn at +90° while E_C is drawn at –90°. Thus, E_L is 180° out of phase with E_C. This illustrates one of the most important characteristics of the series resonant circuit. At resonance, the voltages across the capacitor and coil are of equal magnitude, but they are 180° out of phase. Consequently, E_L exactly cancels E_C. Thus, as far as the source is concerned, the sum of these two voltages is zero. This means that a voltmeter connected between points A and B in Figure 5-7 will read 0 volts.

If the combined voltage drop across X_L and X_C is 0, the applied voltage must be developed across R. That is, if the source voltage is 10 volts, the voltage across R is 10 volts. If you connect a voltmeter across R, it will read 10 volts. However, since the same current must flow through C, if you connect a voltmeter across C, will also read 10 volts. Moreover, a voltmeter placed across L will read 10 volts. At first this may seem to violate Kirchhoff's voltage law. It does not because the 10 volts across C is cancelled by the 10 volts across L. As Figure 5-8 shows, the vector sum of E_L and E_C is 0 volts. This is the first of several strange occurrences which take place in series resonant circuits.

Another strange thing is the apparent disappearance of the coil and the capacitor at resonance. Since the combination of L and C produces no voltage drop, their total reactance or impedance must be zero. That is, the source sees the LC combination as a perfect conductor that has 0 ohms of impedance. Thus, the only opposition to current flow in the circuit is the resistance of R. The source sees no capacitance and no inductance, only resistance.

To easily prove this, apply the impedance formula you learned about earlier. Recall that:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

When $X_L = X_C$, $X_L - X_C = O$. Therefore:

$$Z = \sqrt{R^2 + 0}$$

$$Z = \sqrt{R^2}$$

$$Z = R$$

Thus at resonance, the total impedance is simply the value of R. This means that the current and voltage as viewed by the source are in phase. Consequently, the power factor is 1.

It is important to emphasize again that these conditions occur only at resonance. When the applied frequency is above or below resonance, X_L does not exactly equal X_C. Consequently, the voltage drops across L and C do not completely cancel. In this case, there is some resultant value of reactance.

The third strange thing which happens in series resonant circuits is the most mysterious of all. It is not evident in Figure 5-7 because the value of R is equal to the value of X_L and X_C. However, look at the circuit shown in Figure 5-9. Here, the value of R is much less than that of X_L or X_C. Nevertheless, the circuit is still at resonance because X_L equals X_C.

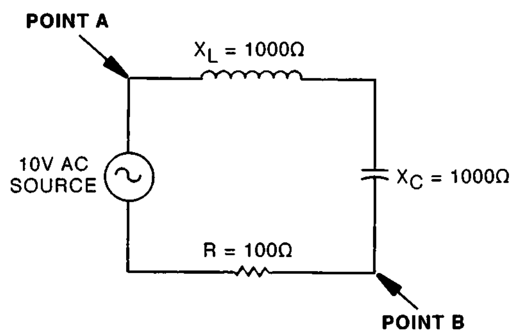


Figure 5-9
R is less than X_L or X_C.

You have seen that the current in a resonant circuit is determined solely by the applied voltage and the value of the series resistance. Thus, in this circuit, $I = \frac{E}{R} = \frac{10\ V}{100\ \Omega} = 0.1$ ampere. This same current flows through C and L. Therefore, the voltage drop across C must be $E_C = I\,(X_C) = 0.1\ A \times 1000\ \Omega = 100\ V$. Also, the voltage drop across L must be $E_L = I\,(X_L) = 0.1\ A \times 1000\ \Omega = 100\ V$. Note that the voltage across L or C is actually ten times higher than the voltage being applied to the circuit.

Once again, this may seem to violate Kirchhoff's voltage law. However, it does not since the 100 volts across L is exactly cancelled by the 100 volts across C. If you connect a voltmeter from point A to point B it will still read 0 volts. But, if you connect the meter across L or C separately, it will read 100 volts.

This ability to produce a voltage higher than the applied voltage is one of the most remarkable characteristics of the series-resonant circuit. This is possible due to the ability of the coil and the capacitor to store energy.

It occurs at resonance any time that the value of R is lower than the value of X_L or X_C. The lower the value of the resistance as compared to the reactance, the higher the voltage across the reactance. If you could entirely eliminate all series resistance, the current in the circuit would theoretically rise to an infinitely high value. The voltage across the coil and the capacitor would also become infinitely high.

In practice, of course, some series resistance is always present. The AC source always has some value of series resistance as will the connecting wires. However, the largest source of series resistance is generally the coil. Most coils are wound from lengths of very small wire. Thus, they have a relatively large value of series resistance. This resistance tends to keep the resonant current down even if there is no separate resistor.

To summarize, the series resonant circuit has several important characteristics. These are listed below:

1. The impedance across the circuit is low and is equal to the series resistance.

2. The current flow is high and is limited only by the series resistance.

3. The applied voltage is dropped by the series resistance.

4. The voltage across the coil or capacitor is equal to the current times the reactance. This voltage may be higher than the applied voltage.

5. The circuit acts resistive. The source current and voltage are in phase and the power factor is 1, or unity.

Programmed Review

35. A series RLC circuit is resonant at the frequency at which X_L equals ___________.

36. (X_C) In a series RLC circuit, the same current flows through all components. When X_L equals X_C, the voltage that is developed across the inductor is the same as that developed across the ___________.

37. (capacitor) The voltage across the inductor ___________ (leads/lags) the current by 90°.

38. (leads) On the other hand, the voltage across the capacitor ___________ (leads/lags) the current by 90°.

39. (lags) Consequently, the voltage across the capacitor is ___________ degrees out of phase with the voltage across the inductor.

40. (180) For this reason, the voltage across the capacitor exactly cancels the voltage across the ___________.

41. (inductor or coil) If you connect a meter across the coil and capacitor, it will read ___________ volts.

42. (0) Because no voltage is developed across the coil-capacitor combination, the total impedance of the coil and capacitor at resonance is ___________ ohms.

43. (0) In a series resonant RLC circuit, the only opposition to current flow is offered by the ___________.

44. (resistance) That is, in a series resonant circuit, the impedance is equal to the ___________.

45. (resistance) In a series resonant circuit with 10 VAC applied, the resistance is 10 ohms. What is the current in the circuit? __________ amperes.

46. (1) If in this same circuit X_L is 120 ohms, what is the voltage drop across X_L? __________ volts.

47. (120) Note that this voltage is __________ times higher than the applied voltage.

48. (12) However, this does not violate Kirchhoff's law since this voltage is exactly cancelled by the voltage drop across the __________.

49. (capacitor) This voltage step-up across the reactance occurs only in series resonant circuits in which X_L or X_C is larger than __________.

50. (R)

Q AND BANDWIDTH IN SERIES-RESONANT CIRCUITS

The series-resonant circuit has two characteristics which you have not learned about yet. These are called *Q* and *bandwidth*. These two characteristics are defined and explained in this section. You learned earlier that Q is a figure of quality for coils. However, the Q used in connection with resonant circuits has additional aspects which you must understand. You also learned about bandwidth in connection with filters. Here, you will learn more about bandwidth.

Q In Series-Resonant Circuits

One of the most important characteristics of a resonant circuit is its Q. Other names for Q include: quality figure, figure of merit, and magnification factor. The Q factor is the ratio of the reactance at resonance to the series AC resistance. That is,

$$Q = \frac{X_L}{R}$$

Or, since at resonance $X_L = X_C$,

$$Q = \frac{X_C}{R}$$

Normally though, you express the reactance in terms of X_L.

In a resonant circuit in which $X_L = X_C = 1000\ \Omega$ and the series AC resistance is $100\ \Omega$; the Q factor is 10 because:

$$Q = \frac{X_L}{R} = \frac{1000\ \Omega}{100\ \Omega} = 10$$

Since Q is the ratio of reactance to resistance, the ohms in each term cancel. Thus, Q is simply a number without any associated units.

In the series resonant circuit, Q is the magnification factor that determines how much the voltage across L or C increases above the applied voltage. For example, if you apply a 1 V peak-to-peak AC signal across a series resonant circuit with a Q of 10, the voltage across L or C at resonance is 10 V peak-to-peak. Thus, the applied voltage, E_{in}, is magnified by the Q factor. Expressed as an equation:

$$E_L = Q \times E_{in}$$

And:

$$E_C = Q \times E_{in}$$

When you know the applied voltage, E_{in}, and the voltage across L or C, E_L or E_C, you can calculate the Q factor with the formula:

$$Q = \frac{E_L}{E_{in}} \quad \text{or} \quad Q = \frac{E_C}{E_{in}}$$

To determine Q, you can measure E_{in} and E_L or E_C and use the above formula. For example, when you measure E_{in} with an AC voltmeter, you find it to be 0.1 volt. You also E_L and find it to be 15 volts. The Q of the circuit must be:

$$Q = \frac{E_L}{E_{in}} = \frac{15\ \text{V}}{0.1\ \text{V}} = 150.$$

When you use this method to determine Q, it generally gives more accurate results than the X_L/R method. The reason for this is that the AC resistance of the circuit is difficult to determine.

Generally, the largest single factor that makes up the series resistance is the AC resistance of the coil. This AC resistance can be much higher than the DC resistance you measure with an ohmmeter. This makes it difficult to measure the AC resistance of the coil directly.

You will recall that a coil has a Q factor of its own. If the only series resistance in a series resonant circuit is that of the coil, the Q of the circuit is the same as that of the coil. The Q of the coil is the highest possible value of Q that a resonant circuit can have. If you add additional series resistance, the Q of the circuit will be less than the Q of the coil.

While it is difficult to measure directly the AC resistance of a series resonant circuit, you can compute the value from known or measured circuit quantities. For example, a series resonant circuit develops 10 volts across a 1 Henry coil at 100 Hz with a 0.1 volt AC input. Find the Q and the AC resistance.

$$Q = \frac{E_L}{E_{in}} = \frac{10\text{ V}}{0.1\text{ V}} = 100$$

You know that $Q = \frac{X_L}{R}$. Consequently: $R = \frac{X_L}{Q}$. You saw that Q is 100. Thus, if you find X_L, you can determine R.

$$X_L = 2\pi fL$$

$$X_L = 6.28\ (100\text{ Hz})\ (1\text{ H})$$

$$X_L = 628\ \Omega$$

Therefore:

$$R = \frac{X_L}{Q}$$

$$R = \frac{628\ \Omega}{100}$$

$$R = 6.28\ \Omega$$

This shows some of the reasons that Q is important. However, Q is also important to determine the bandwidth of a resonant circuit.

Bandwidth and Q

Resonant circuits are selective. They respond more readily to their resonant frequency, f_O, than to other frequencies. While the resonance effects are greatest at f_O, these same effects exist to a smaller extent at frequencies slightly above and below f_O. Thus, a resonant circuit actually responds to a band of frequencies. The width of this band of frequencies is called the bandwidth of the resonant circuit.

MEASURING BANDWIDTH

Figure 5-10 illustrates how bandwidth is measured. This graph shows the current that is passed by a series resonant circuit at various frequencies below, at, and above the resonant frequency. Naturally, maximum current flows at the resonant frequency. In this example, f_O is 1000 Hz and the maximum current is 10 mA.

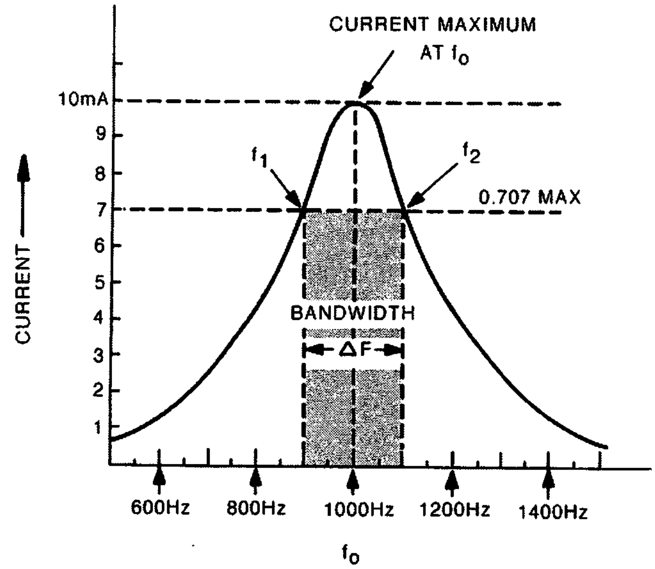


Figure 5-10
Bandwidth is measured between
half-power points.

The bandwidth of the series resonant circuit is generally considered to include that group of frequencies with a response 70.7 % of maximum. In the example, frequencies which produce a current of 7.07 mA or higher are considered within the bandwidth. This band of frequencies extends from f_1 (900 Hz) to f_2 (1100 Hz).

The *bandwidth* is defined as the width of this band of frequencies. Consequently the bandwidth (BW) is $f_2 - f_1$, or 1100 Hz − 900 Hz = 200 Hz. That is, the bandwidth is the width of the band of frequencies which produce a response of 70.7% of maximum current.

HALF-POWER POINTS

You may wonder why the 70.7% points were chosen to indicate the bandwidth. Actually this is a very convenient point to use because it represents the point at which the power in the circuit is exactly one-half the maximum value. Thus, the points marked f_1 and f_2 in Figure 5-10 are referred to as *half-power points.*

An example demonstrates that the power in a circuit drops to one-half when the current drops to 70.7%. Consider a circuit in which the resistance is 2000 ohms and the current is 10 mA. The power is: $P = I^2R = 0.01^2 \times 2000 = 0.0001 \times 2000 = 0.2$ W. Now assume that the current drops to 70.7% of maximum or to 7.07 mA. The power drops to: $P = I^2R = 0.00707^2 \times 2000 = 0.00005 \times 2000 = 0.1$ W. This is one-half the previous power. Thus, when you reduce the current to 70.7%, the power reduces to 50%. For convenience then, the bandwidth is measured between half-power points.

BANDWIDTH EQUALS f_O/Q

With the bandwidth that is measured between the half-power points, an interesting relationship exists between the bandwidth, the resonant frequency, and the value of Q. This relationship is expressed by the equation:

$$BW = \frac{f_O}{Q}$$

This states that the bandwidth equals the resonant frequency divided by the Q.

For the example shown in Figure 5-10, the Q is 5 because:

$$BW = \frac{f_O}{Q}$$

$$BW = \frac{1000 \text{ Hz}}{5}$$

$$BW = 200 \text{ Hz}$$

The equation states that the bandwidth is directly proportional to the resonant frequency, but inversely proportional to the value of Q.

The curves shown in Figure 5-11 illustrate that the bandwidth increases as the value of Q decreases. When the value of Q is high, the current in the circuit is relatively high. The resonant circuit responds to a very narrow band of frequencies. The resonant frequency is 100 kHz. Thus, if the Q is 50, the bandwidth is:

$$BW = \frac{f_o}{Q} = \frac{100\text{ kHz}}{50} = 2\text{ kHz}$$

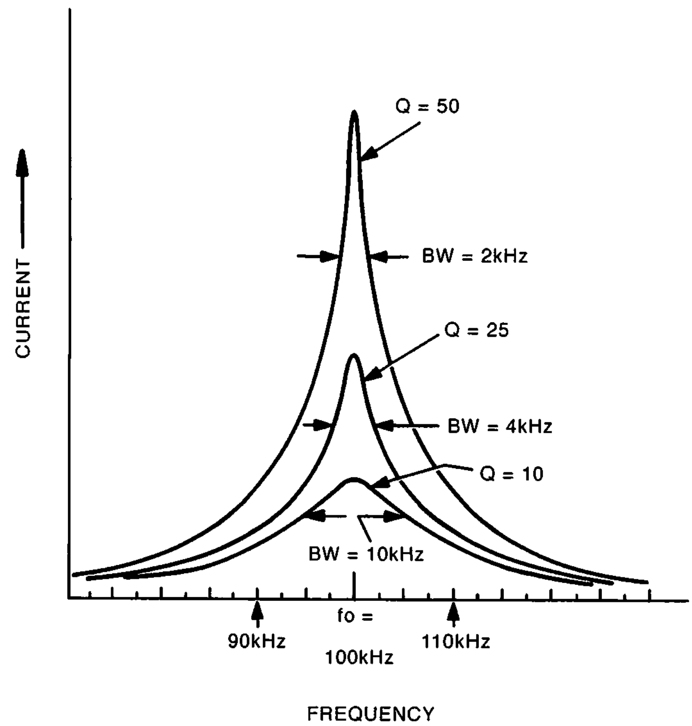


Figure 5-11
Bandwidth increases as Q decreases.

Note what happens to the curve when the Q reduces to 25. The current is lower and the curve is somewhat broader. The bandwidth increases to:

$$BW = \frac{f_o}{Q} = \frac{100\text{ kHz}}{25} = 4\text{ kHz}\,.$$

When the Q reduces to 10, an even broader response curve results. The current is relatively low and the bandwidth is:

$$BW = \frac{f_o}{Q} = \frac{100\text{ kHz}}{10} = 10\text{ kHz}$$

Figure 5-12 shows three circuits which produce curves like those shown in Figure 5-11. The three circuits are identical except for the value of the resistance. The value of R determines the Q of the circuit. This, in turn, determines the bandwidth. Notice that the value of R does not affect the resonant frequency, only the Q and bandwidth. As the value of R in creases, the Q decreases and the bandwidth increases.

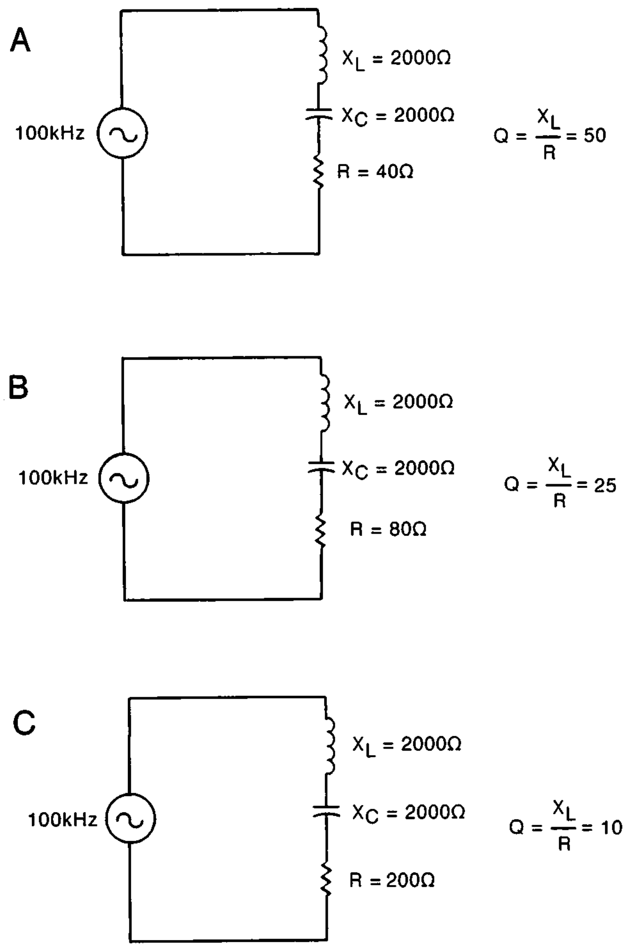


Figure 5-12
Effects of resistance.

Programmed Review

51.	The Q of a series resonant circuit is generally defined as the ratio of the reactance to the series AC resistance. The formula for Q is: Q = ____________ .
52.	($Q = \frac{X_L}{R}$ or $Q = \frac{X_C}{R}$) You can also think of Q as a magnification factor that determines how much the voltage across L or C is increases above the applied voltage. Thus, if E_{in} is 5 volts and the Q is 10, the voltage across the capacitor is ____________ volts.
53.	(50) Therefore, you can express Q in terms of E_{in} and E_C. The formula is ____________ .
54.	($Q = \frac{E_C}{E_{in}}$) Q determines the width of the band of frequencies to which a resonant circuit responds. That is, the bandwidth of a series resonant circuit is determined largely by the ____________ of the circuit.
55.	(Q) The bandwidth of a series resonant circuit is measured at "half-____________" points.
56.	("half-power") These are the points at which the current falls to ____________ percent of its maximum value.
57.	(70.7) The resonant frequency (f_O) and the Q determine the bandwidth. The formula is BW = ____________ .
58.	($BW = \frac{f_O}{Q}$) While the values of L and C determine the resonant frequency, the Q is generally determined by the ____________ in the circuit.
59.	(resistance) The higher the resistance, the lower the Q and the broader the ____________ .
60.	(Bandwidth)

EXPERIMENT 7

Series Resonance

OBJECTIVES: *To calculate the resonant frequency for a series RLC circuit.*

To graph the frequency response curve for a series-resonant RLC circuit.

To compare the calculated values of a resonant frequency with the measured values.

To compute the Q and bandwidth of a series-resonant circuit.

Introduction

In this experiment you will verify that, at resonance, the current is maximum and is determined by the resistance in the circuit. You will also demonstrate that the voltage across the LC combination is minimum. You will prove that the individual voltage across L or C can be higher than the applied voltage. Finally, you will investigate how changes in the values of L, C, and R affect the characteristics of the circuit.

Material Required

Heathkit Analog Trainer
Oscilloscope
AC Voltmeter
Masking tape
1 — .001 μF ceramic capacitor
1 — .01 μF Mylar capacitor
1 — 107 mH variable inductor (#45-610)
2 — 1000 Ω, 1/2-watt resistors (brown-black-red)

Procedure

1. Set the Generator section of the Trainer so you can adjust the frequency between 2 kHz and 20 kHz. Then turn on the Trainer and adjust the Generator section for a sine wave output of 2 kHz.

   NOTE: In this and the following steps, where you will measure a frequency or a voltage at a frequency, use the oscilloscope to measure the period of one cycle and calculate the frequency. For example; the period for one cycle of a 20 kHz sine wave is 50 μs/cm (1 ÷ 20,000 Hz). Remember to choose a time base that allows you stretch one cycle over several centimeters in the display so you can measure the period with greater accuracy.

2. Measure the sine wave output with your AC voltmeter. Slowly increase the frequency up to 20 kHz as you monitor the voltage with your AC voltmeter. Note that the output is nearly constant for all frequencies. The output voltage at 20 kHz is __________ volts.

3. Disconnect your voltmeter from the Trainer. Then construct the circuit shown in Figure 5-13A. Be sure to center the core in the variable inductor's coil. Then, stick masking tape to the Trainer, around the Generator frequency control. You will mark the tape to identify various frequencies in this experiment.

4. Connect the AC voltmeter across R_1. Adjust the frequency control on the Trainer until the voltage across R_1 is maximum. The voltage across R_1 is: E_{R1} = __________ VAC. Is this the resonant point? __________.

5. Use a pencil to mark the point on the masking tape next to the frequency dial pointer where the maximum voltage across R_1 occurs. The resonant frequency appears to be about __________ Hz. With the frequency control set to this frequency, measure the applied AC input voltage between the SINE and GND terminals. The voltage is E_{in} = __________ VAC. Compare this with the value you measured in step 2. Has the voltage changed? __________. How do you account for this? ____________________
   ____.

6. Use the values of L_1 and C_1 given in Figure 5-13A to compute the resonant frequency of the circuit. f_O = __________ Hz. How does this compare with the frequency you approximated in step 5? ____________________
   ____
   ____.

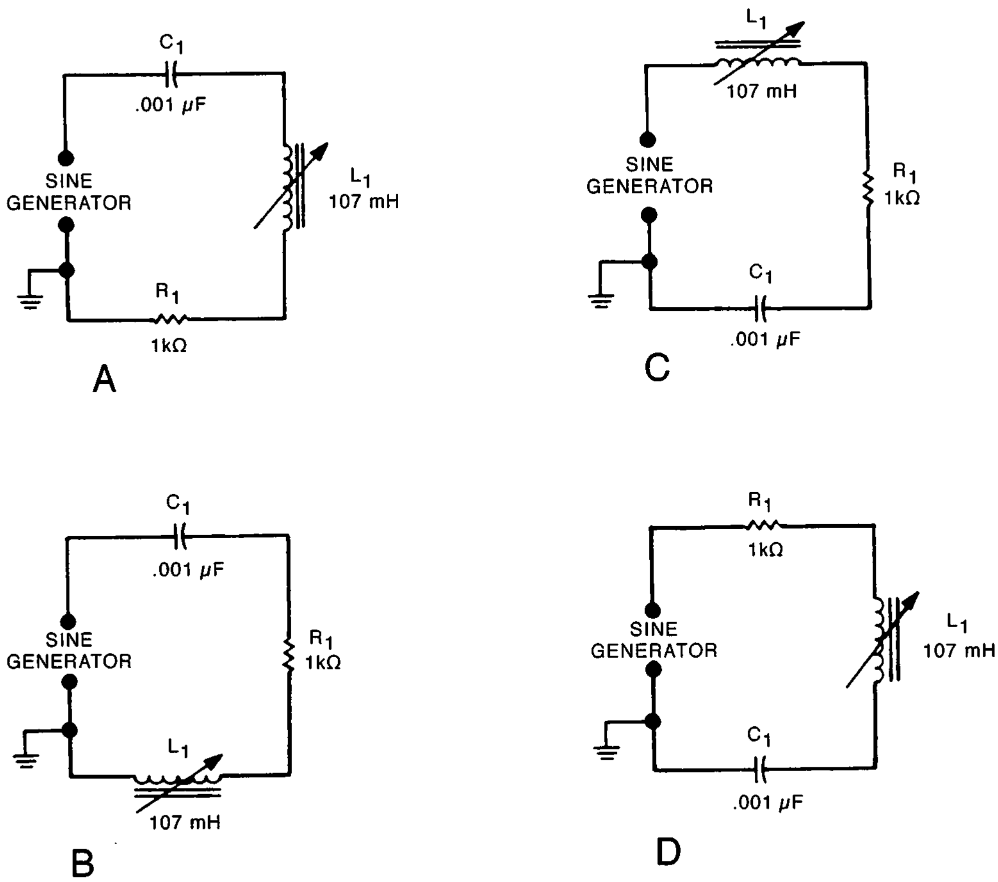


Figure 5-13

7. Reconstruct the circuit so that the components are arranged as shown in Figure 5-13B. The position of the components does not affect the characteristics of the circuit. After you do this, turn the frequency control to the 2 kHz position, change the voltmeter to the 50-volt scale, and connect the voltmeter across L_1. Now, turn the frequency control knob clockwise until the voltage across L_1 is maximum.

   Is the frequency control knob now set at the position that you marked in step 5? ___________.

   The voltage across L_1 at this point is: E_L = ___________ volts. Is this voltage higher than the generator output voltage, E_{in}, you measured in step 5? ___________.

8. Reconfigure the circuit so that the position of the components matches those shown in Figure 5-13C. Return the frequency control knob to the 2 kHz position and leave the voltmeter set to the 50-VAC scale. Connect the voltmeter across capacitor C_1. Rotate the frequency control knob in the clockwise direction until the voltage across the capacitor is maximum.

   Is the frequency control now in the position you marked in step 5? __________.

   The voltage across C_1 at this point is: E_C = __________ VAC.

   Is E_C approximately equal to E_L? __________.

9. Finally, reconfigure the circuit so that the position of the components matches the position of the components in Figure 5-13D. Turn the frequency control to the 2 kHz position and connect the voltmeter across the capacitor and the coil. Now adjust the frequency control until the voltmeter indication is minimum.

   Is the frequency control knob in the position you marked in step 5? __________.

   The voltage across C_1 and L_1 is __________ VAC

   Do the capacitor and inductor voltages completely cancel one another? __________. If so, why? ______________________________
   ____
   ____.

10. Use the equation $Q = \frac{E_L}{E_{in}}$ to compute the Q of the circuit. Use the value of E_{in} you measured in step 5. Q = __________.

11. Use the equation $X_L = 2\pi fL$ to compute the X_L of the circuit. Use 107 mH as the value of L and the frequency you computed in step 6 as the value of f. X_L = __________ ohms.

12. Use the equation $X_C = \frac{1}{2\pi fC}$ to compute the value of X_C. Use 0.001 µF as the value of C and the frequency you computed in step 6 as the value of f. X_C = __________ ohms. Are X_L and X approximately equal? __________.

13. Compute the bandwidth of the circuit with the formula $BW = \frac{f_o}{Q}$. BW = ____________ Hz. What are the frequencies at the half-power points? ____________ Hz and ____________ Hz.

14. Connect your voltmeter across the capacitor and carefully set the frequency control for maximum voltage across C. E_C = ____________ VAC.

15. Multiply this voltage by 0.707 to find the voltage at the half-power points. $E_C \times 0.707$ = ____________ VAC.

16. Slowly turn the frequency control counterclockwise until the voltage across C is the value you computed in step 15. What is the frequency at this point? ____________ Hz. Mark this point on the frequency dial.

17. Slowly turn the frequency control clockwise, through the resonant point and beyond, until the voltage across C is the value you computed in step 15. What is the frequency at this point? ____________ Hz. Mark this point on the frequency dial.

Discussion

In the previous steps, you observed many of the characteristics of a series resonant circuit. In step 2, you measured the AC output voltage for the Trainer sine generator. After you constructed the circuit and adjusted the frequency control until the circuit was at resonance, you measured the sine generator output again in step 5. You should have noticed a change in the output. This occurs because the series circuit has a very low impedance at resonance. This low impedance loads the generator and causes a lower output voltage.

The current through a series resonant circuit is maximum. In step 4, when you adjusted the frequency control so that the voltage drop across R_1 was maximum, you were actually determining the resonant frequency of the circuit. From Ohm's Law, you know that the maximum voltage drop occurs when maximum current moves through the circuit.

In step 6, you used the nominal inductor and capacitor values to compute the resonant frequency of the circuit. Your computed value should have been 15,370 Hz. The actual resonant frequency will vary somewhat due to component tolerances and the stray capacitance of the coil and the generator.

In step 7, you adjusted the frequency control until the voltage across the coil was maximum. You observed the position of the frequency control to confirm that the voltage across the coil is maximum at the circuit's resonant frequency. In step 8, you saw that the same is true of the voltage across the capacitor.

You should have noticed that E_L and E_C were actually higher than the generator voltage. If you used a high-impedance meter to make your measurement, you discovered that the voltage was several times higher. This occurs because the voltage across the reactive components is a result of the current through the component and the component's reactance. At resonance, the circuit current is controlled entirely by the resistance in the circuit.

In step 9, however, you saw that the voltage across the inductor and the capacitor tend to cancel one another. Remember, current leads voltage in a capacitor and current lags voltage in an inductor. Because of this, the capacitive and inductive voltages are 180° out of phase with each other, and cancel. In reality, complete cancellation does not occur because there is a built-in resistance in the coil that develops a voltage drop of its own. This built-in resistance is the ohmic resistance of the wire that was used when the inductor was manufactured.

You then used the measured values of E_L and E_{in} to computed the Q of the circuit in step 10. In step 11 you computed the value of X_L. In step 12, you computed X_C and found that it is the same as X_L.

In step 13 you divided the resonant frequency, 15,370 Hz, by the value of Q to compute the bandwidth. Typically the bandwidth is about 2400 Hz. Thus, the circuit responds to the band of frequencies between 14170 Hz and 16570 Hz. In steps 14 through 17, you marked the points on the dial which corresponded to the upper and lower limits of this band of frequencies. You are now ready to continue your experiment, to see how the circuit behavior is affected when you change component values.

Procedure (continued)

18. Replace the 1000 ohm resistor, R_1, with a jumper wire. Try to predict the effect this will have on:

Resonant frequency	________
Q	________
E_C	________
E_L	________
E_{in}	________
Bandwidth	________

19. Set the frequency control to the 2 kHz position and connect your voltmeter across C_1. Carefully adjust the frequency control until E_C is maximum. Note the frequency at which this occurs. Did the resonant frequency change? ________.

20. Observe the voltage across the capacitor. E_C = ________ VAC. How did E_C change from the value you measured in step 14? ________.

21. Reconfigure your circuit so it appears like the one shown in Figure 5-13B. Remember, R_1 is replaced by a jumper wire. Set the frequency control to the 2 kHz position and connect the voltmeter across L_1. Adjust the frequency control until E_L is maximum. Note the frequency at which resonance occurs. E_L = ________.

22. With the frequency control set to the resonant frequency, measure the generator output voltage. E_{in} = ________ VAC.

23. Use the value of E_L you measured in step 21 and the value of E_{in} you measured in step 22 to compute the new value of Q. $Q = \frac{E_L}{E_{in}}$ = ________.
Has the circuit Q increased or decreased? ________.

24. Compute the new bandwidth with the formula BW = ___________ Hz. Has the bandwidth increased or decreased? ___________.

25. Multiply the value of E_L you found in step 21 by 0.707. $E_L \times 0.707$ = ___________ VAC.

26. Slowly turn the frequency control counterclockwise until the voltage across L is the value you computed in step 25. At this point, is the frequency dial above or below the lower half-power point you marked earlier? ___________.

27. Slowly turn the frequency control clockwise through the resonant point to the upper half-power point. Is this point above or below the upper half-power point you marked earlier? ___________.

28. Replace the .001 μF capacitor with the .01 μF capacitor. Compute the new resonant frequency. ___________ Hz. Has the frequency increased or decreased? ___________. Adjust the frequency control until the voltage you measure across the coil is maximum to set the generator to the new resonant frequency. Does the dial reading agree with the computed frequency? ___________.

Discussion

In step 18 you replaced the 1000 ohm resistor with a jumper wire. You then predicted the effects this would have on the various circuit parameters. Now check your predictions.

In step 19, you verified that the resonant frequency did not change. You expect this since the values of L and C solely determine the resonant frequency.

Without the resistance of R_1, more current flowed through L and C. Consequently, the voltage drop across both L and C increased. You proved this in steps 20 and 21. Both E_L and E_C increased in value.

In step 22, you measured the output of the generator. The generator output decreased because the LC circuit had a lower impedance than the previous RLC circuit. This created a greater loading effect.

Since E_L increased even with E_{in} lower, the Q of the circuit must have increased. You proved this when you calculated the value of Q in step 23.

In step 24 you computed the new bandwidth. The bandwidth decreased because the Q increased. You verified this in steps 25, 26, and 27.

Finally, in step 28 you increased the value of the capacitor. This resulted in a decrease in resonant frequency. The new resonant frequency was about 4862 Hz. The dial reading you obtained in step 28 should be somewhere close to this point.

Procedure (continued)

29. Reconstruct the circuit as shown in Figure 5-13D (be sure to reinstall a 1 kΩ resistor into the circuit and change the capacitor value back to .001 μF). Set the generator range switch so that you can adjust your frequency between 2000 Hz and 20 kHz. Connect the AC voltmeter across C_1. Be sure to observe proper grounding.

    You will plot the response curve of your RLC circuit. To obtain the best results, adjust your generator through the range of frequencies and watch the voltage drops **before you record any values**. This will give you an idea of how the circuit responds.

30. Adjust the frequency control knob for 2000 Hz. The frequency is ___________ kHz. The voltage across the capacitor (E_C) is ___________ VAC.

31. Rotate the frequency control knob so that it is half way between 2000 Hz and 20 kHz. The frequency is ___________ kHz. The voltage across the capacitor is ___________ VAC.

32. Rotate the frequency control knob clockwise to 20 kHz. The frequency is ___________ kHz and the voltage is ___________ VAC.

33. Now that you have a general idea of the increments of voltage and frequency for your series RLC circuit, use your oscilloscope and AC voltmeter to plot at least 20 different points across the frequency range. Record the values on a separate piece of paper.

34. Refer to Figure 5-14. Establish a scale for the vertical (E_C) axis that allows you to plot your maximum and minimum voltages across most of the graph. Then, plot the values you measured on the graph.

35. Connect the plotted points with a continuous line to form a response curve. At what frequency is E_C maximum? ___________ Hz. What is the value of E_C at this frequency? ___________ VAC.

36. Multiply this value of E_C by 0.707. $E_C \times 0.707 =$ ___________ VAC. Mark this voltage on the curve at the points above and below resonance.

37. Place a second 1 kΩ resistor in series with R_1 so that the total resistance in series with L and C is 2 kΩ.

38. Repeat steps 30 through 36 for this new circuit. Plot the new response curve in Figure 5-14.

39. Switch the Trainer off and remove the circuit components from the Trainer.

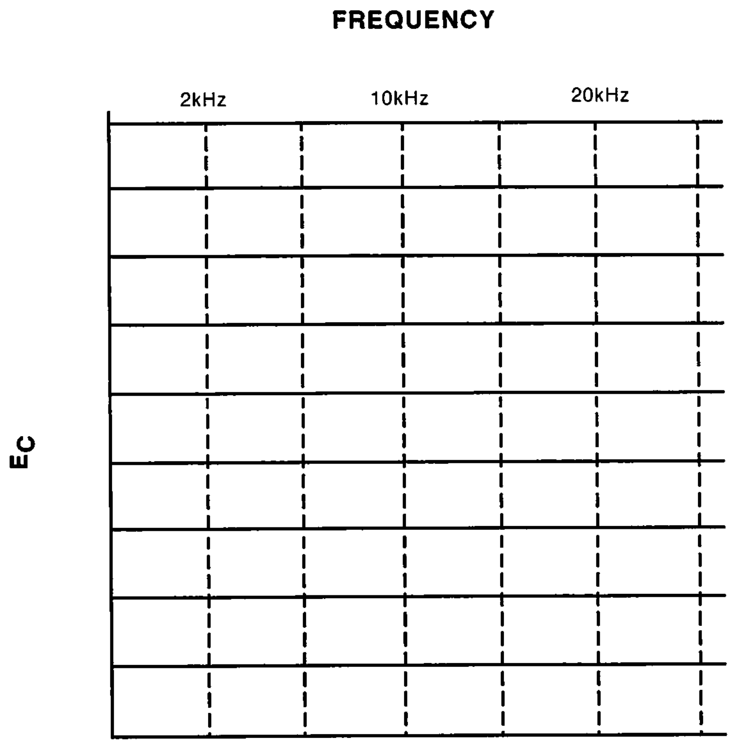


Figure 5-14
Plot your values here.

Discussion

In this part of the experiment you drew two response curves for the series resonant circuit. Typical response curves are shown in Figure 5-15. Your curves should resemble these. Three things about these curves are particularly interesting. First, maximum voltage always occurs at resonance. Second, when R increases the amplitude of E_C decreases. Third, the bandwidth increases when R increases.

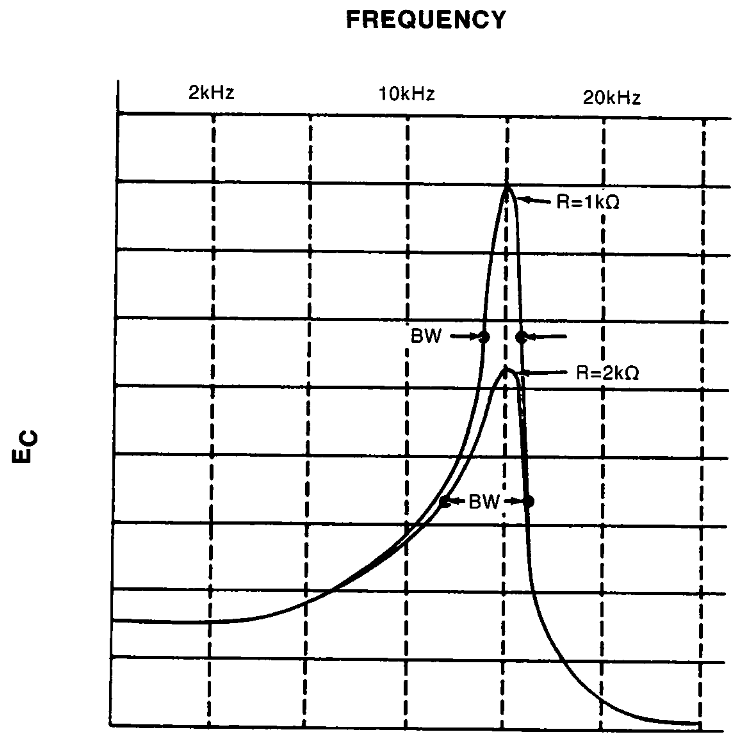


Figure 5-15

Typical curves for the series resonant circuit.

PARALLEL RESONANCE

Up until now you were concerned with only resonant circuits in which the capacitor is in series with the inductor. In this section, you will consider another type of resonant circuit called a parallel resonant circuit. When the capacitor is placed in parallel with the inductor, the characteristics of the resonant circuit change completely.

Ideal Circuit

A parallel resonant circuit is shown in Figure 5-16. You know that the circuit is in the resonant condition because X_L equals X_C. Thus, the applied AC signal is at the proper frequency to cause the circuit to resonate.

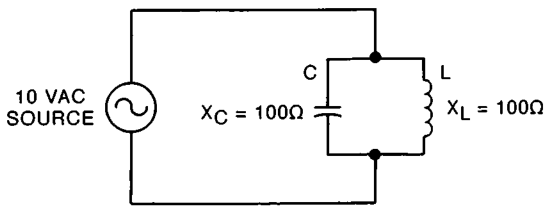


Figure 5-16
Parallel resonant circuit.

To simplify the explanation of this circuit, initially assume that L and C are ideal components so that there is no resistance in the circuit. Of course, in practical circuits there is always some resistance and you will consider its effects later. But for now, you will see what would happen in an ideal parallel resonant circuit.

When you temporarily disconnect the capacitor from the circuit as shown in Figure 5-17A, you can use Ohm's Law to determine the current through the coil:

$$I_L = \frac{E}{X_L} = \frac{10\ V}{100\ \Omega} =$$

This current must be supplied by the AC source. Since L is a pure inductor, I_L must lag the applied voltage by 90°.

If you reconnect the capacitor and disconnect the inductor as shown in Figure 5-17B, you can determine the current through the capacitor with Ohm's Law:

$$I_C = \frac{E}{X_C} = \frac{10\ V}{100\ \Omega} = 0.1\ A$$

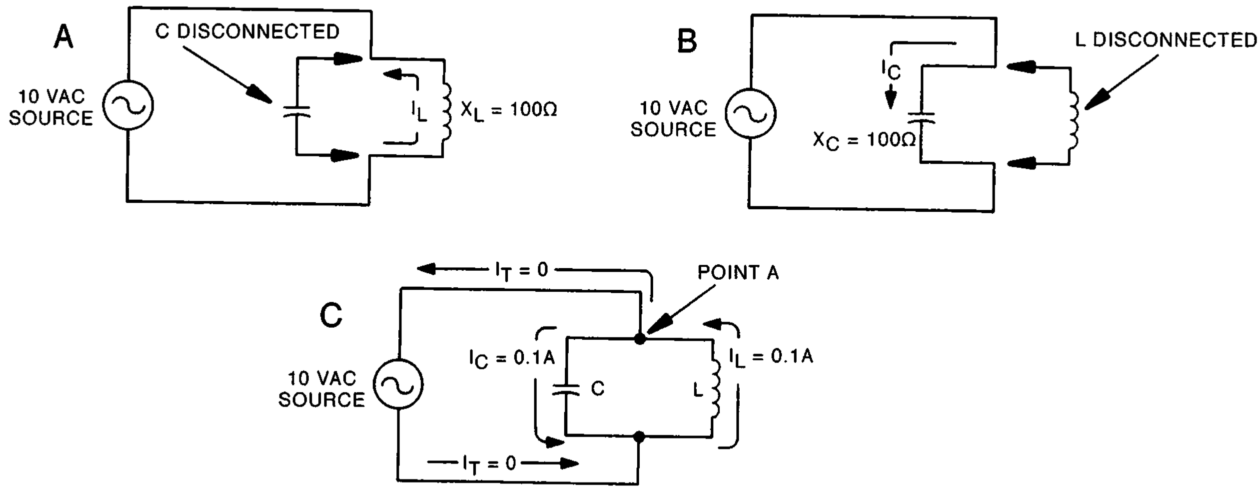


Figure 5-17
Current in the parallel resonant circuit.

However, you will recall that in a capacitor the current leads the voltage by 90°. Thus, I_C must lead the applied voltage by 90°. Now consider the operation of the complete circuit. If I_C leads the applied voltage by 90° and I_L lags the applied voltage by 90°, I_C must be 180° out of phase with I_L. This means that when the current is flows in one direction through L, an equal current must flow in the opposite direction through C.

At the instant when 0.1 A is flows up through L, exactly 0.1 A must flow down through C. Now when you apply Kirchhoff's current law to point A in Figure 5-17C, you discover that no current flows into or out of the source. That is, the same current that flows up through L also flows down through C and no current flows to or from the source. On the next alternation, the current flows up through C and down through L, but still no current flows in the external circuit. The current simply oscillates back and forth between the capacitor and the coil.

In the ideal parallel resonant circuit, the source voltage is required only to start the oscillation. Once started, you can disconnect the source and the oscillations will continue indefinitely. As you learned earlier, this is true only if there are no losses in the circuit.

Now consider how the parallel resonant circuit appears to the AC source. The AC voltage is applied across the LC combination and yet no current flows to the source. Consequently, as far as the source is concerned, the circuit appears to be open. That is, it appears to have infinite impedance.

Flywheel Effect

The ability of a parallel resonant circuit to sustain oscillation after you remove the source voltage is called the flywheel effect. It gets this name because the action is similar to that of a mechanical flywheel. Once the mechanical flywheel has been started, it tends to keep going until it is stopped by friction or some outside force. The flywheel effect of the parallel resonant circuit is illustrated in Figure 5-18.

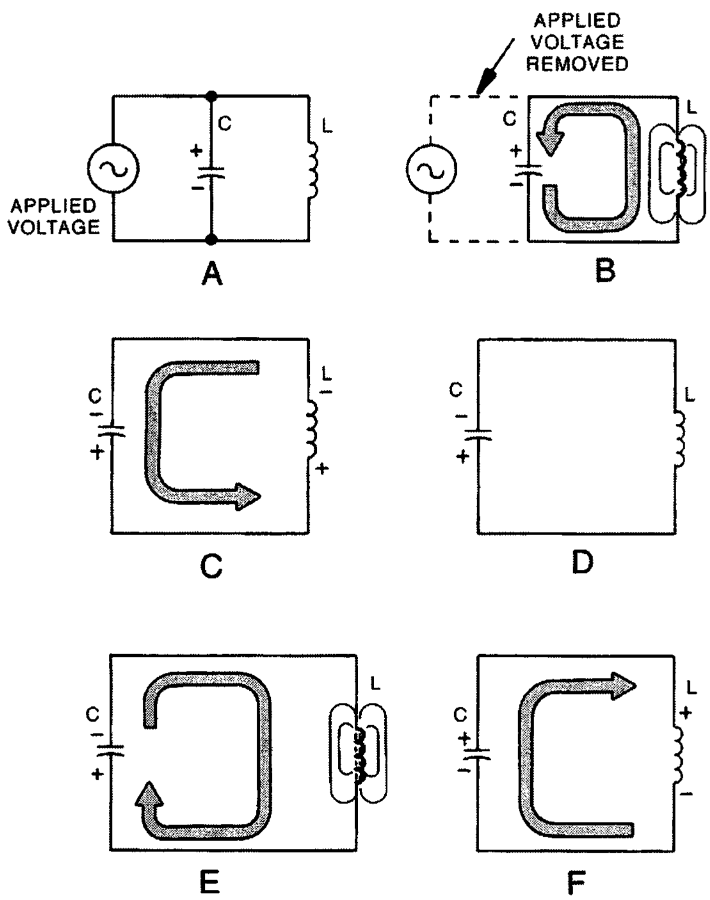


Figure 5-18
The flywheel effect.

Initially, energy is supplied to the circuit by an AC source. Once it starts, the energy is alternately stored by the capacitor and then by the coil. You will now pick up the action at the point where C is fully charged as shown in Figure 5-18A.

You can remove the applied voltage since it has supplied the necessary starting energy. As shown in Figure 5-18B, the capacitor begins to discharge through L. As current flows through L, a magnetic field builds up around the inductor.

When C is discharged, the current through L tends to stop. Consequently, the magnetic field around L collapses which induces an EMF with the polarity shown in Figure 5-18C. This keeps the current flowing in the same direction and charges C to the polarity shown.

After the magnetic field collapses, the condition shown in Figure 5-18D exists. Here, the capacitor is again fully charged. At the next instant, the capacitor begins to discharge. This time, the current flows in the opposite direction through the coil as shown in Figure 5-18E. This causes a magnetic field of the opposite polarity to build up around L.

When C again discharges, the current through L tries to stop and the magnetic field collapses. As shown in Figure 5-18F, an EMF is induced which tends to keep current flowing in the same direction. Thus, C is again charged to its initial polarity.

At this point the cycle repeats itself. As you can see, the energy is simply interchanged between the capacitor and the coil. Initially, the energy is stored as an electrostatic field in the capacitor. Then, it is stored as a magnetic field around the inductor. Theoretically, neither the capacitor nor the coil dissipates energy. Therefore, the oscillations would continue indefinitely if there were no losses in the circuit.

Because a circuit of this type can store energy, it is commonly called a tank circuit.

Practical Tank Circuits

The ideal tank circuit has no resistance and no losses of any kind. Unfortunately, such a tank circuit does not exist. The capacitor, the coil, and the interconnecting wires all have resistance. Normally, though, only the resistance of the coil is high enough to be important. Thus, in reality, you must analyze practical tank circuits as if there were a resistor in series with the inductor as shown in Figure 5-19. R represents the resistance of the coil.

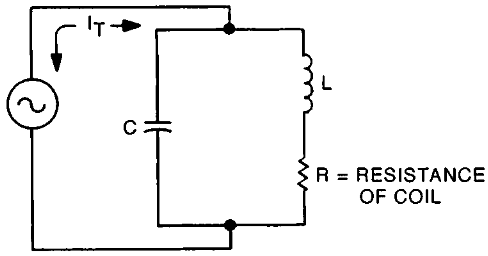


Figure 5-19
Practical tank circuit.

Unlike reactance, resistance dissipates power. As the current oscillates between the coil and the capacitor, the resistor dissipates some of the power in the form of heat. Consequently, some of the energy is removed from the tank circuit during each cycle. For this reason, in a practical tank circuit, the oscillations will quickly die out if the AC source is disconnected. Figure 5-20 shows how the voltage waveform across the tank circuit would look. Each cycle gets progressively weaker as the resistance gradually dissipates the energy stored in the circuit. The waveform that is produced is called a damped sine wave.

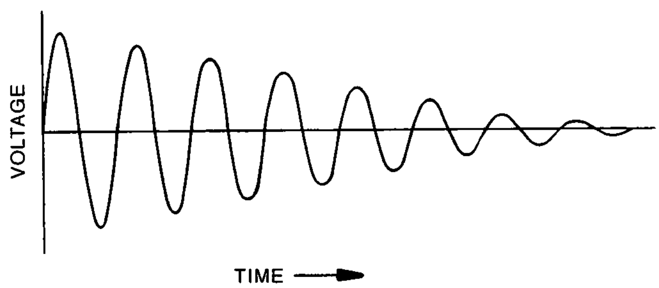


Figure 5-20
Damped sine wave.

Because there is power loss in the circuit, the source must supply power to make up for the loss. Thus, the AC source provides just enough power to make up for that lost by the resistance. The result is that some current flows from the AC source to the tank circuit. If the resistance value in the tank is high, more power is dissipated, and the current from the source is higher.

This may seem to contradict Ohm's Law since current is inversely proportional to resistance. The resistance does limit the circulating current within the tank. However, in doing so, it consumes power. This power must be supplied by the AC source. Therefore, the current from the source must increase.

Q in Parallel-Resonant Circuits

In the series resonant circuit you divided the applied voltage, E_{in}, into either E_C or E_L to find Q. This does not work in the parallel resonant circuit since E_{in} is applied directly across both C and L. In the parallel resonant circuit, you are concerned with current rather than with voltage. Thus, in the parallel resonant circuit, you divide the source current into the tank current to determine Q. Recall that in a good tank circuit the source current is quite low, while the circulating current can be very high. Therefore,

$$Q = \frac{I_{TANK}}{I_{SOURCE}}$$

If the source current is 1 mA and the tank current is 100 mA, the Q is:

$$Q = \frac{I_{TANK}}{I_{SOURCE}} = \frac{100\text{ mA}}{1\text{ mA}} = 100$$

As with the series resonant circuit, you can also express Q as the ratio of X_L, or X_C, to R. That is: $Q = \frac{X_L}{R}$. R is the total AC resistance within the tank. It can be somewhat higher than the value of R you measure with an ohmmeter.

In the parallel resonant circuit, you can think of Q as a magnification factor. However, in this case it is not the voltage that is being magnified but the impedance. Because the source current is minimum at resonance, the impedance of the tank circuit is maximum at resonance. The impedance of the tank equals the reactance of L or C times the Q. That is: $Z_{TANK} = X_L\,(Q)$ or $Z_{TANK} = X_C\,(Q)$. If the value of X_L, or X_C, at resonance is 1000 ohms and the Q is 100, the impedance of the tank is:

$$Z_{TANK} = X_L\,(Q)$$

$$_{TANK} = 1000\ \Omega \times 100$$

$$Z_{TANK} = 100{,}000\ \Omega \text{ or } 100\ k\Omega$$

You can transpose the above equation to develop another useful equation. That is:

$$Q = \frac{Z_{TANK}}{X_L}$$

Thus you have three equations for Q. These are:

$$Q = \frac{I_{TANK}}{I_{SOURCE}} \qquad Q = \frac{X_L}{R} \qquad Q = \frac{Z_{TANK}}{X_L}$$

Of these equations, the last one is the most useful to determine Q. It is difficult to use the first equation because it is hard to measure the AC current. The second equation also presents problems because it is hard to determine the total AC resistance.

To use the last equation, all you need are the values of X_L and Z_{TANK}. You can easily compute X_L if you know the value of L. Furthermore, you can use method shown in Figure 5-21 to easily determine the impedance of the tank.

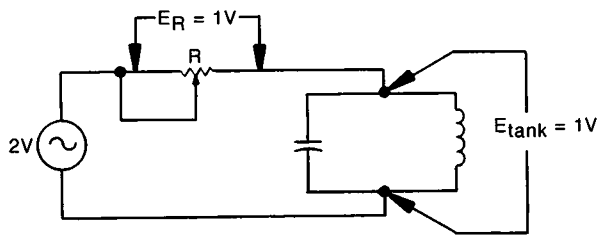


Figure 5-21
When $E_R = E_{TANK}$, $Z_{TANK} = R$

Here, a variable resistor has been placed in series with the tank circuit. At the resonant frequency, you adjust the resistor until the voltage across the resistor equals the voltage across the tank. That is: $E_R = E_{TANK} = 1/2\ E_{in}$. At this point, R drops the same amount of voltage as the tank. Thus, R must be equal to the impedance of the tank. You now disassemble the circuit and measure the value of R with an ohmmeter. This tells you the value of Z_{TANK}. You can now use this value in the equation to determine the Q of the circuit.

Bandwidth in Parallel-Resonant Circuits

Like the series resonant circuit, the parallel tank circuit responds to a band of frequencies rather than a single frequency. Figure 5-22 shows a typical response curve. Note that this curve has the same shape as the response curve shown earlier for the series resonant circuit. However, if you examine Figure 5-22 more closely, you see that it shows the impedance of the circuit rather than the current through the circuit.

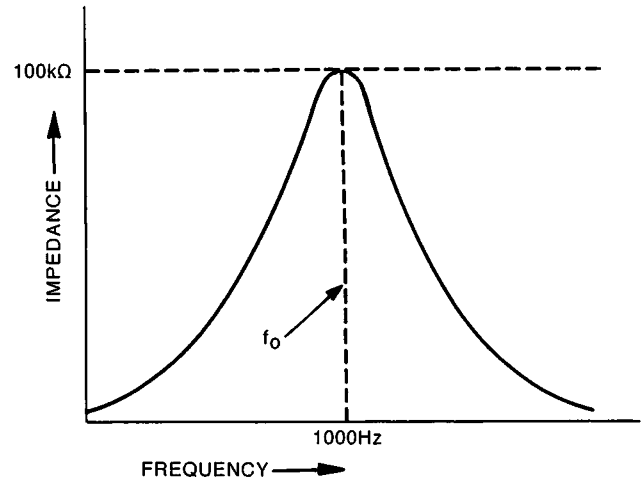


Figure 5-22
Response curve of parallel resonant circuit (impedance vs. frequency).

At the resonant frequency, the impedance is maximum. Below resonance, the coil offers a low reactance and the impedance falls off. Above resonance, the capacitor offers a low reactance and the impedance again falls off.

Because the source or line current is inversely proportional to the impedance, the current response curve has the shape shown in Figure 5-23. Note that the line current decreases as you approach the resonant frequency.

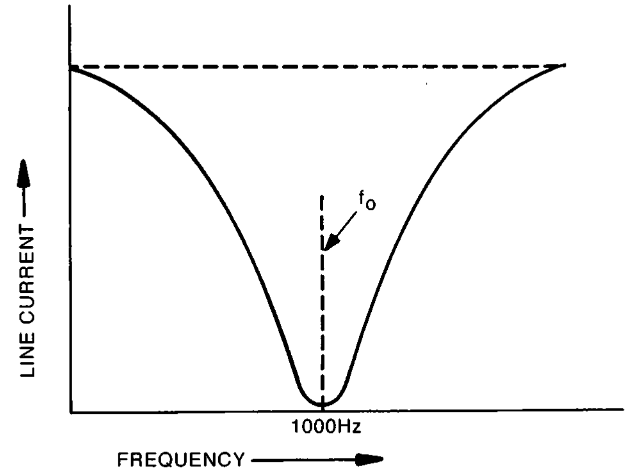


Figure 5-23
Response curve of parallel resonant circuit (current vs. frequency).

As is case with the series-resonant circuit, the Q of the circuit determines the width of the band of frequencies to which the circuit responds. You determine the bandwidth with the formula: $BW = \frac{f_o}{Q}$. If a parallel resonant circuit has a resonant frequency of 1000 Hz and a Q of 20, the bandwidth is:

$$BW = \frac{f_o}{Q} = \frac{1000\text{ Hz}}{20} = 50\text{ Hz}$$

Thus, it responds to the band of frequencies between 975 Hz and 1025 Hz.

Often, a parallel-resonant circuit is more selective than you would like. That is, it responds only to a very narrow band of frequencies. In these cases, you can connect a relatively small value resistor across the tank circuit as shown in Figure 5-24A to increase the bandwidth. The resistor provides an alternate path for line current. Thus, the line current increases. Recall that $Q = \frac{I_{TANK}}{I_{LINE}}$. For this reason, Q is inversely proportional to the line current. If the line current increases, Q must decrease. However, the formula $BW = \frac{f_O}{Q}$ shows that the bandwidth is inversely proportional to Q. Thus, if Q decreases, the bandwidth increases. Therefore, when you connect a resistor across the tank circuit, you increase the bandwidth. This is often called *loading* the tank circuit.

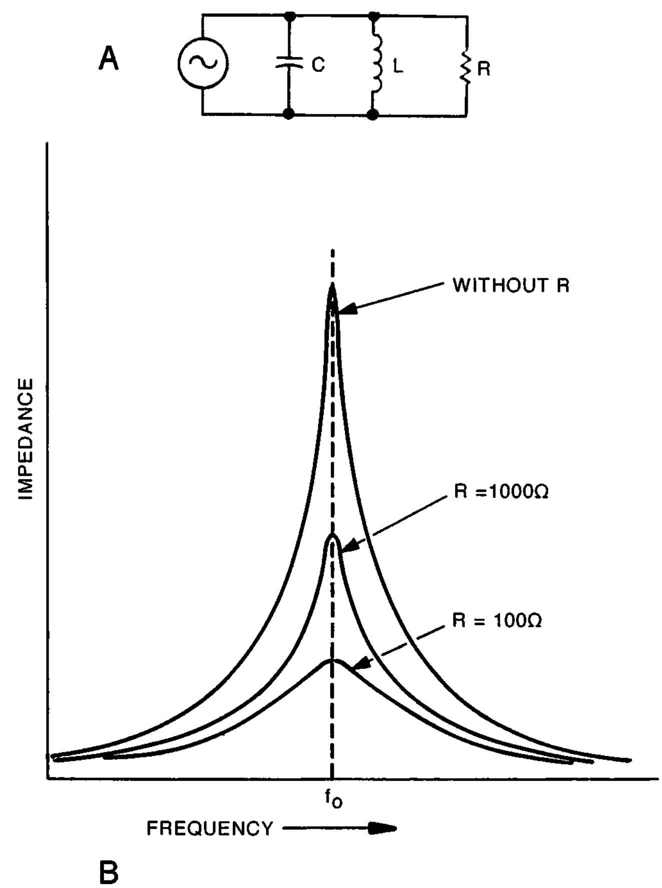


Figure 5-24
By loading the tank circuit
you can increase the bandwidth.

Figure 5-24B shows the effect that the resistor can have. Without the resistor, the impedance is extremely high and the circuit responds only to a very narrow band around the resonant point. When you add a 1000 ohm resistor, the additional parallel path for current reduces the impedance and broadens the bandwidth. A 100 ohm resistor reduces the impedance still further and stretches the bandwidth even more.

Distributed Capacitance and Self Resonance of Coils

As you learned earlier, every coil has a certain value of distributed capacitance. That is, the coil acts as if a small value capacitor is connected in parallel. At some frequency, the coil and this value of distributed capacitance form a parallel resonant circuit. At this frequency, the coil is referred to as self-resonant. Thus, a single coil can have the characteristics of a parallel resonant circuit at its self-resonant frequency.

Power Factor and the Parallel-Resonant Circuit

In industrial applications of AC electronics, especially where large motors are used, power factor is an important consideration. To see why this is so, you will first look at a typical industrial situation.

Figure 5-25 depicts the entire circuit load for a small factory: a number of motors, lighting fixtures, and other components which are connected in parallel. This load is connected to a 120-volt, 60 Hz source. The line current is 50 amperes and the power factor for the entire circuit is .707. Remember, power factor equals the true power divided by the apparent power, and is the same as the cosine of the phase angle.

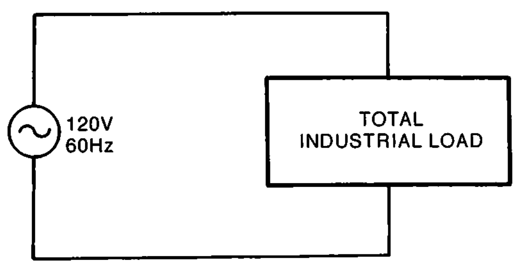


Figure 5-25

Since the motors are inductive, the load appears to be inductive. Figure 5-26 shows the current vector diagram for the circuit. Note that the line current, 50 amps, is the current through the impedance of the entire circuit and is shown on the hypotenuse of the current triangle. You use the trigonometric relationships that were described earlier to calculate the current through the resistive portion of the circuit, 35.35 amps, and the current through the reactive portion of the circuit, 35.35 amps.

At any rate, the industrial customer must pay the utility company for the power that appears to be used in the circuit. You use the line current and the voltage applied to calculate the amount of power that is consumed. This "power" is:

$$120 \text{ volts} \times 50 \text{ amps} = 6000 \text{ volts/amps}$$

Note that the power company considers the power used in the factory to be the same as the number of volt/amps or apparent power for the circuit. As you know, the inductive portion of the circuit does not actually consume power. It merely stores energy and then releases it. This, however, is not taken into consideration when the power consumption is calculated.

There is a way to correct this obvious problem. Remember, the current through a resonant parallel circuit is minimum. That is, in a parallel-resonant circuit, the line current is equal to the current through the resistive portion of the circuit. All other current, that is, the current through the inductive and capacitive portions of the circuit, circulates through the circuit but does not contribute to the line current.

In order to bring the calculated power use more into line with the amount of power actually being used, it is necessary to add a capacitor in parallel with the inductive circuit. Since X_L and X_C are equal at resonance, you must first determine the inductive reactance of the circuit before you can determine the size of the necessary capacitor.

To do this, apply Ohm's Law to the inductive portion of the circuit. The inductive reactance is:

$$X_L = \frac{E}{I} = \frac{120 \text{ volts}}{35.35 \text{ amps}} = 3.39 \text{ ohms}$$

Since X_L and X_C are equal:

$$3.39 = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 60 \times C}$$

Now transpose:

$$C = \frac{1}{6.28 \times 60 \times 3.39} = .000783 \text{ f}$$

When you add a 783 μF capacitor in parallel with the industrial circuit, the circuit becomes a parallel-resonant circuit. Now, when you calculate power consumption, only the true power is indicated. The power consumed by the parallel resonant circuit is:

$$P = 120 \text{ volts} \times 35.35 \text{ amps} = 4242 \text{ watts}$$

Capacitor Ratings

The capacitors that are actually used to correct the power factor in industrial applications are rated in kilovars. To determine the size of the capacitor necessary to correct a particular circuit, you must know the inductive power that is used in the circuit. For the example, this is:

$$\text{reactive power} = 120 \text{ volts} \times 35.35 \text{ amps} = 4242 \text{ VARS}$$

To calculate the rating of the capacitor for the circuit, simply divide the number of VARS by 1000 like this:

$$\frac{4242}{1000} = 4.242 \text{ kilovars}$$

A 4.424 kilovar capacitor is needed to correct the circuit.

Calculated Power Savings

Utility companies usually bill customers for the number of kilowatt hours that are used during a given period. To convert the power used into kilowatt hours, you use the formula:

$$\text{kilowatt hours} = \frac{\text{watts}}{1000} \times \text{time}$$

Now calculate the power saving for the typical industrial customer for an 8-hour day. Without a corrected power factor, the industry uses:

$$\text{kw hrs} = \frac{6000 \text{ w}}{1000} \times 8 \text{ hrs} = 48 \text{ kw hrs}$$

Now, with a corrected power factor, the power company supplies the industry with:

$$\text{kw hrs} = \frac{4242 \text{ w}}{1000} \times 8 \text{ hrs} = 33.94 \text{ kw hrs}$$

As you can see, the savings for a single day amounts to somewhat more than 10 kw hrs, or almost a 23% reduction in consumed power.

Programmed Review

61.	A parallel LC circuit is resonant at the frequency where X_L equals ___________.
62.	(X_C) At resonance, a high current can flow between the capacitor and the coil. These oscillations can continue even after you remove the source voltage. This phenomenon is called the ___________ effect.
63.	(flywheel) In an ideal circuit, the oscillations could continue indefinitely without additional energy from an outside source. However, in practical circuits, the energy is quickly dissipated by the ___________ in the circuit.
64.	(resistance) Some resistance always exists in a tank circuit. Generally, the largest source of resistance is the AC resistance of the ___________.
65.	(coil or inductor) If the circuit is to continue to oscillate, the energy that is dissipated by the resistance must be constantly replaced by the C source. Thus, some ___________ always flows from the source.
66.	(current). However, at resonance, the current supplied by the source is ___________ than the current flowing in the tank. smaller /larger
67.	(smaller) In fact, at resonance, the line current is ___________ (minimum/maximum) but the tank current is ___________ (minimum /maximum).
68.	(minimum, maximum) Because the line current is minimum, the tank circuit offers a high ___________ to the line current.
69.	(impedance) In parallel-resonant circuits, Q is defined in terms of the line current (I_{LINE}) and the tank current (I_{TANK}). The formula for Q is: Q = ___________.

70. ($Q = \frac{I_{TANK}}{I_{LINE}}$) If the line current is 2 mA and the tank current is 100 mA, the Q of the circuit is ___________.

71. (50) The impedance of the tank equals the reactance times the Q. That is: $Z = X_L (Q)$. You can rearrange this equation to express Q in terms of Z and X_L. Thus, Q = ___________.

72. ($Q = \frac{Z}{X_L}$) A practical tank circuit responds to a band of frequencies. The resonant frequency and Q determine the width of this band. The equation is: BW = ___________.

73. ($BW = \frac{f_O}{Q}$) A circuit with an f_O of 64 kHz and a Q of 16 has a bandwidth of ___________.

74. (4 kHz) Thus, it responds to frequencies between ___________ kHz and ___________ kHz.

75. (62 kHz and 66 kHz) You can add a ___________ in parallel with the tank to broaden bandwidth of a tank circuit.

76. (resistor) This ___________ (increases/decreases) the impedance and ___________ (increases/decreases) the Q of the circuit.

77. (decreases, decreases)

EXPERIMENT 8

Parallel Resonance

OBJECTIVES: *To compare tank voltage drops with line voltage drops.*

To calculate the resonant frequency of a tank circuit.

To explain the relationship between the tank impedance and the Q of a parallel resonant circuit.

Introduction

You can demonstrate many of the characteristics of the parallel-resonant circuit through experimentation. In this experiment, you will examine the characteristics and operation of two parallel-resonant circuits.

Material Required

Heathkit Analog Trainer
Oscilloscope
Volt-ohmmeter
1 — 107 mH coil (#45-610)
1 — .01 μF capacitor
1 — .0022 μF capacitor
2 — 4700 Ω, 1/2-watt resistors (yellow-violet-red)

Procedure

1. Construct the circuit shown in Figure 5-27. Make sure the inductor's core is centered in the coil.

2. Use the circuit values given to compute the resonant frequency. f_O = __________ Hz.

3. Set your AC voltmeter or oscilloscope to a range that will allow you to measure the maximum output voltage of your Trainer's sine wave Generator.

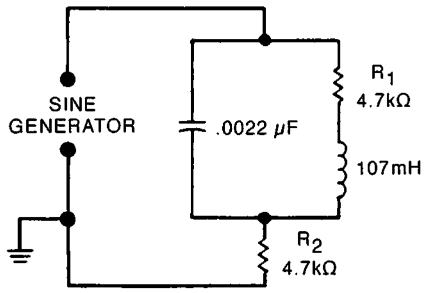


Figure 5-27

4. Set the Trainer Generator range to produce a sine wave output of approximately 20 kHz. Then, adjust the frequency control until there is a minimum voltage drop across R_2. The frequency is __________ Hz. The frequency that you just measured should be close to the calculated value.

5. With the frequency dial at the point you set in step 4, measure the voltage across R_2 and record it in the space provided. E_{R2} = __________ . Reconfigure the circuit so it appears like the one in Figure 5-28. To do this, interchange the leads from the generator. Measure the voltage across R_1 and record the value in the space providcd. E_{R1} = __________. Which voltage is greater, E_{R1} or E_{R2}? __________. Since the two resistors have the same value, which has more current flowing through it? __________.

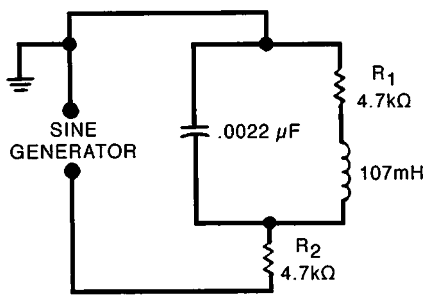


Figure 5-28

6. Interchange the leads from the generator once more so that the circuit appears like the one shown in Figure 5-27. Connect the voltmeter across resistor R_2 and replace resistor R_1 with a jumper wire. What happens to the voltage across R_2 when R_1 is removed from the circuit? __________
____.

Discussion

In the first part of the experiment, you constructed the parallel-resonant circuit shown in Figure 5-27. Note that R_1 is in the tank circuit while R_2 is in series with the tank. The computed resonant frequency is about 10,480 Hz. In step 3 you adjusted the frequency control until the voltage across R_2 was minimum. This occurred when the line current was minimum. In other words, it occurred at resonance. The resonant frequency you read from the dial should have been reasonably close to the value you computed in step 2.

In step 5, you compared the voltage across the 4.7 kΩ resistor in the tank, R_1, with the voltage across the 4.7 kΩ resistor in the line, R_2. The voltage across R_1 should have been higher since, at resonance, the circulating tank current was greater than the line current.

In step 6 you shorted out the resistor in the tank while you monitored E_{R2}. You found that E_{R2} decreased. This means that the current through R_2 decreased. At first this may seem to contradict Ohm's Law. After all, normally when you short out a resistor in one branch of a parallel circuit you expect the total current to increase. However, this case is different. Due to the resonance phenomenon, shorting R_1 **does** increase the current within the tank. However, recall that the only thing the line current does is to make up for the losses within the tank. The main loss within the tank is the energy dissipated by R_1. When you short R_1, it dissipates no energy and the losses within the tank are less. Consequently, the line current decreases.

You can also explain the decrease in line current in another way. Recall that $Q = \frac{X_L}{R}$. When you short R_1 to decrease R, Q increases. In a parallel-resonant circuit, Q is the impedance magnification factor. Thus, if Q increases, so does the impedance of the tank. This increase in impedance causes a decrease in the line current. These explanations are simply two different ways of saying the same thing.

Procedure (continued)

7. Disassemble the previous circuit. Connect an ohmmeter between pins 1 and 2 of the 100 k ohm potentiometer on the Trainer. Adjust the potentiometer until the ohmmeter indicates 20 k ohms.

8. Leave the potentiometer set to this point while you construct the circuit shown in Figure 5-29.

9. Use the circuit values given to compute the resonant frequency. f_O = ___________ Hz.

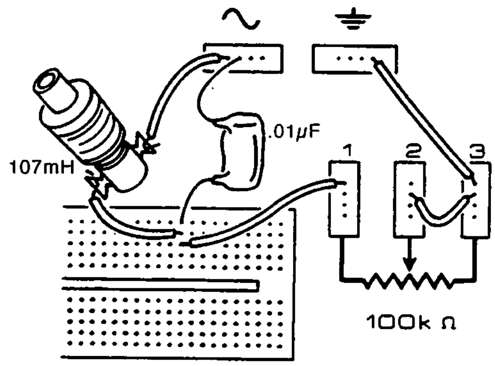


Figure 5-29
Circuit for steps 7 through 19.

10. Connect the AC voltmeter between pins 1 and 2 of the 100 kΩ potentiometer.

11. Set the generator range switch to high. Adjust the frequency control for minimum voltage across the potentiometer. The frequency dial reads __________ Hz. Compare this with the resonant frequency you computed in step 9. Are the two frequencies about the same? ________________.

12. Leave the frequency control set to this point. Measure the voltage between the SINE and GND terminals of the generator. E_{in} = __________ VAC.

13. Divide this value by two. $\frac{E_{in}}{2}$ = __________ VAC.

14. Reconnect your voltmeter between pins 1 and 2 of the 100 kΩ potentiometer. Adjust the 100 kΩ potentiometer until the meter indicates the value you computed in step 13.

15. Without moving the arm of the 100 kΩ potentiometer, disconnect the circuit. Use an ohmmeter to measure the resistance between pins 1 and 2 of the 100 kΩ potentiometer. The resistance is __________ ohms.

16. Since this resistance dropped one half on E_{in}, the impedance of the tank (Z_{TANK}) must have dropped the other half of E_{in}. Therefore, Z_{TANK} = __________ ohms.

17. Use the formula $X_L = 2\pi fL$ to find the X_L of the coil. X_L = __________ ohms.

18. Use the formula $Q = \frac{Z_{TANK}}{X_L}$ to find the Q of the circuit. Q = __________.

Discussion

In this part of the experiment, you constructed the circuit shown in Figure 5-30. The computed resonant frequency of this circuit is about 4862 Hz. In step 11, the frequency control should have been set somewhere in the vicinity of this point on the dial. Next, you adjusted the 100 kΩ potentiometer so that it dropped one half of the applied voltage. Since the tank also dropped one half of the applied voltage, the impedance of the tank was the same as the resistance of the potentiometer. Thus, to find the impedance you measured the value of the potentiometer. Typically, the impedance should have been about 50,000 ohms. Once you know Z_{TANK}, you could easily find the Q of the circuit.

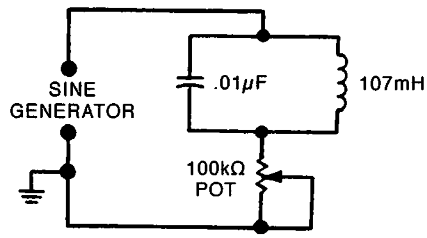


Figure 5-30
Schematic diagram of the circuit shown in Figure 5-29.

The computed X_L of the coil was 3267 ohms. Thus, the Q was about:

$$Q = \frac{Z_{TANK}}{X_L}$$

$$Q = \frac{50{,}000}{3267}$$

$$Q = 15$$

These are typical values and can vary somewhat depending upon component tolerances, the accuracy of your ohmmeter, and voltmeter loading.

LC FILTERS

In an earlier unit you saw that R_C and R_L circuits pass some frequencies more easily than others. When an R_C or R_L circuit is especially designed to be frequency selective, the resulting circuit is called a filter.

In this unit you saw that LC circuits are frequency selective. Therefore LC circuits can make good filters.

Types of Filters

There are several types of filters used in electronics. Generally, you can place a basic filter circuit in one of four categories.

A *band-pass* filter is designed to pass a narrow band of frequencies while it rejects both higher and lower frequencies. These filters are used in radios and TV receivers to pass the frequencies of the desired station while they block the frequencies of all other stations.

A *band-stop* filter is designed to pass all frequencies except a narrow band. You can use this type of filter to clip out an annoying frequency without interfering with wanted frequencies.

A *low-pass* filter is used to attenuate all frequencies above a certain cutoff frequency. Thus, it passes low frequencies but blocks high frequencies.

A *high-pass* filter has the opposite characteristics. It passes signals above the cutoff frequency but blocks those below.

All four types of filters are commonly used. The frequencies which are blocked or passed depend upon the component values used and how the components are arranged. You will now look at some typical filters beginning with the band-pass filter.

Band-Pass Filter

A very simple band-pass filter is shown in Figure 5-31A. The filter is the series-resonant circuit that is formed by L and C. R_L is the load to which the voltage is applied. At the resonant frequency, the series-resonant circuit has a very low impedance. Thus, it drops very little of the applied voltage, E_{in}. Most of the voltage is developed across R_L. Consequently, E_{out} is high at the resonant frequency.

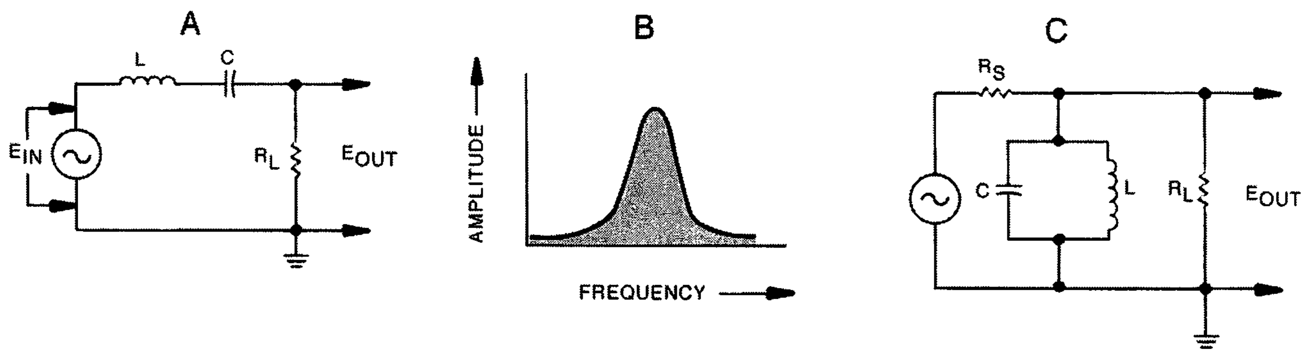


Figure 5-31
Band-pass filter.

Below the resonant frequency, the X_C of the capacitor is higher than the resistance of R_L. Consequently, most of E_{in} is dropped by C. This leaves only a small voltage across R_L. Thus, E_{out} is a low voltage.

Above the resonant frequency, the X_L of the coil is higher than R_L. Therefore, most of the voltage is dropped across the coil and E_{out} is again a low voltage.

Figure 5-31B shows how the circuit responds to a band of frequencies. At the resonant frequency of L and C, E_{out}, is quite high. Above and below resonance E_{out} drops off quickly to a low voltage.

Figure 5-31C shows that you can also use the parallel-resonant circuit as a band-pass filter. The series-resonant circuit is connected in series with the output, while the parallel-resonant circuit is connected across the output. The reason for this becomes evident if you remember the characteristics of the parallel-resonant circuit.

At resonance, the impedance of the tank circuit is extremely high. Consequently, very little current flows through the tank circuit and most of the current flows through R_L. The current through R_L is maximum at resonance.

Below resonance, the X_L of the coil is quite small compared to the value of R_L. Thus, most current flows through L and very little flows through R_L. Above resonance, most of the current flows through the capacitor which leaves little current for R_L. That is, above and below resonance, R_L is partially shorted out by the low impedance of the tank. Thus, most of the applied voltage is dropped across R_S. However, at resonance, the impedance of the tank is high and R_L is no longer shorted.

Figure 5-32A shows another type of band-pass filter. This one uses a transformer. Recall that the windings of a transformer have an inductance value like any other coil. Therefore, you can connect a capacitor across one of the windings to form a parallel-resonant circuit.

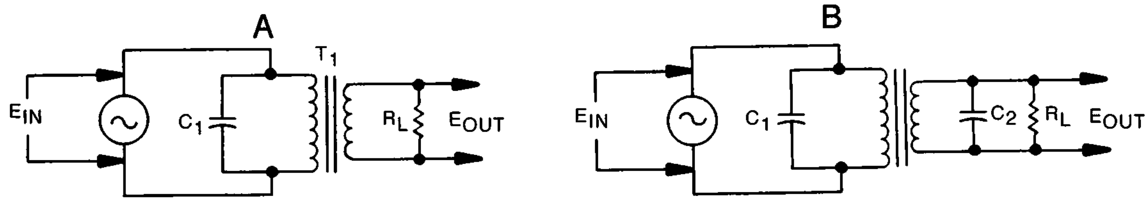


Figure 5-32
A tuned transformer can act as a band-pass filter.

In Figure 5-32A, C_1 is connected across the primary of the transformer. This causes the transformer to respond much more readily to the resonant frequency than to other frequencies. Recall that at resonance the circulating current within the tank is at its maximum value. This heavy current in the primary of the transformer develops a strong magnetic field. Consequently, maximum voltage is coupled to the secondary at the resonant frequency. Frequently both the primary and the secondary are tuned as shown in Figure 5-32B. The bandwidth of this circuit depends mainly upon three factors: the Q of the tuned primary circuit, the Q of the tuned secondary circuit, and the coefficient of coupling. When the coefficient of coupling is close to 1, the bandwidth is extremely broad. However, when the coefficient of coupling is very low, the bandwidth is quite narrow.

Band-Stop Filter

The response of the band-stop filter is opposite to that of the band-pass filter. That is, the band-stop filter stops, attenuates, or rejects the frequency to which it is tuned.

Figure 5-33A shows a simple band-stop filter. Here L and C form a parallel-resonant circuit which is in series with the load, R_L. At resonance, the impedance of the tank circuit is much higher than the resistance ofR_L. Consequently, most of E_{in} is dropped across the tank and very little voltage is available at the load. Above and below resonance, the resistance of R_L is higher than the impedance of the tank. Therefore, most of E_{in} is developed across R_L. Figure 5-33B shows the response of the circuit. The Q of the resonant circuit determines sharpness of the curve.

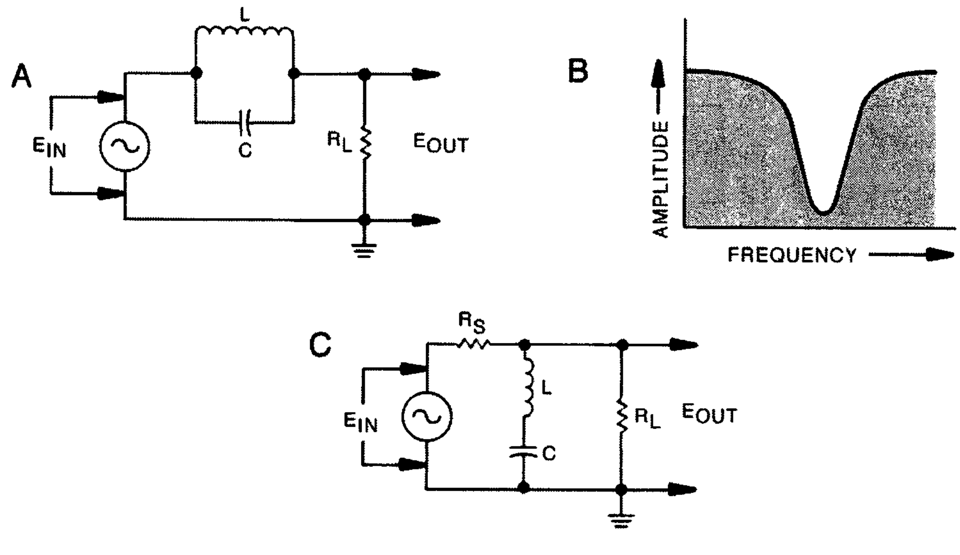


Figure 5-33
The band-stop filter.

Another circuit that produces about the same response is shown in Figure 5-33C. Here, a series-resonant circuit is connected across the load. At resonance, the series-resonant circuit offers a very low impedance to current flow. This shorts most of the current around the load. Most of the applied voltage is dropped across R_S. Above and below resonance, the impedance of the filter is much higher and R_L is no longer shorted out.

Low-Pass Filter

A low-pass filter passes all frequencies below a certain cutoff frequency. A simple low-pass filter is shown in Figure 5-34A. At low frequencies X_L is lower than the resistance of R_L. Thus, most of E_{in} is developed across R_L. Furthermore, the X_C of the capacitor is high at low frequencies. Thus, most of the current flows through R_L. As you can see, E_{out} is quite high at low frequencies.

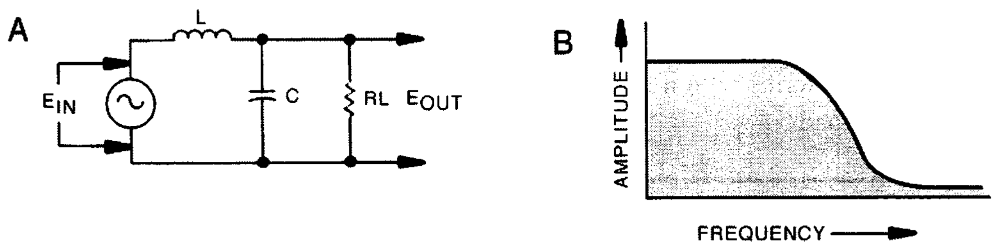


Figure 5-34
Low-pass filter.

The situation reverses at high frequencies. The X_L of the coil increases and drops most of applied voltage. Only a slight voltage is developed across R_L. Furthermore, the X_C of the capacitor decreases so that most of the current is shunted around R_L. Hence, the filter effectively blocks high-frequency signals. The response of the filter is shown in Figure 5-34B.

High-Pass Filter

The high-pass filter passes all frequencies above a certain cutoff frequency. Figure 5-35 shows the high pass filter and its response curve. At high frequencies X_C is low and X_L is high. Thus, the capacitor and coil have little effect. Most of E_{in} is developed across R_L. At low frequencies, X_C is high and X_L is low. Thus, the high value of X_C drops most of the applied voltage while the low value of X_L tends to short R_L. Thus, the circuit passes high frequencies but blocks lower frequencies.

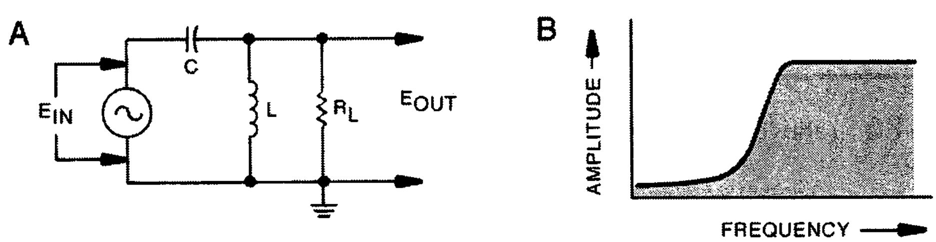


Figure 5-35
High-pass filter.

Programmed Review

78. A circuit that is designed to pass some frequencies and block others is called a ___________ .

79. (filter) Many filters use coils and capacitors together to produce a desired frequency response. A series resonant LC circuit has minimum impedance at resonance. Thus, if this type of filter is connected in series with a load, it will pass the ___________ frequency to the load.

80. (resonant) This is an example of a band-___________ filter.

81. (pass) If the same series-resonant circuit is placed across the load, it will short out the load at the resonant frequency. This is an example of a ___________ filter.

82. (band-stop) You can also use the parallel-resonant circuit as a filter. When it is connected in series with a load, it forms a ___________ filter.

83. (band-stop) On the other hand, you can connect the parallel-resonant circuit across the load to form a ___________ filter.

84. (band-pass) A low-pass filter blocks all frequencies ___________ (above/below) its cutoff frequency.

85. (above) A high-pass filter passes all frequencies ___________ (above/below) its cutoff frequency.

86. (above) In a low-pass LC filter, the ___________ (capacitor/coil) is connected in with the load but the ___________ (capacitor/coil) is connected across the load.

87. (coil, capacitor) In the high-pass LC filter, the ____________ is connected in series with the load, but the ____________ is connected across the load.

capacitor/coil

capacitor/coil

88. (capacitor, coil) Figure 5-36 shows the response curves of the four basic types of filters. Match the following:

1.	band-pass	A.	Figure 5-36A
2.	band-stop	B.	Figure 5-36B
3.	High-pass	C.	Figure 5-36C
4.	Low-pass	D.	Figure 5-36D

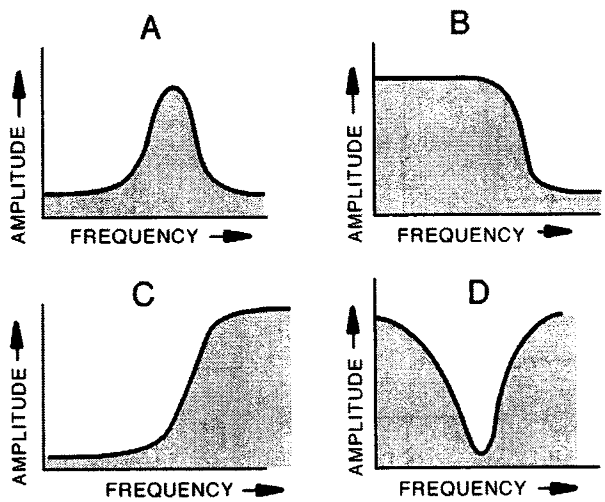


Figure 5-36

89. (1-A, 2-D, 3-C, 4-B) Figure 5-37 shows six types of filters. Match the following:

A.	Figure 5-37A	1.	band-pass
B.	Figure 5-37B	2.	band-stop
C.	Figure 5-37C	3.	high-pass
D.	Figure 5-37D	4.	low-pass
E.	Figure 5-37E		
F.	Figure 5-37F		

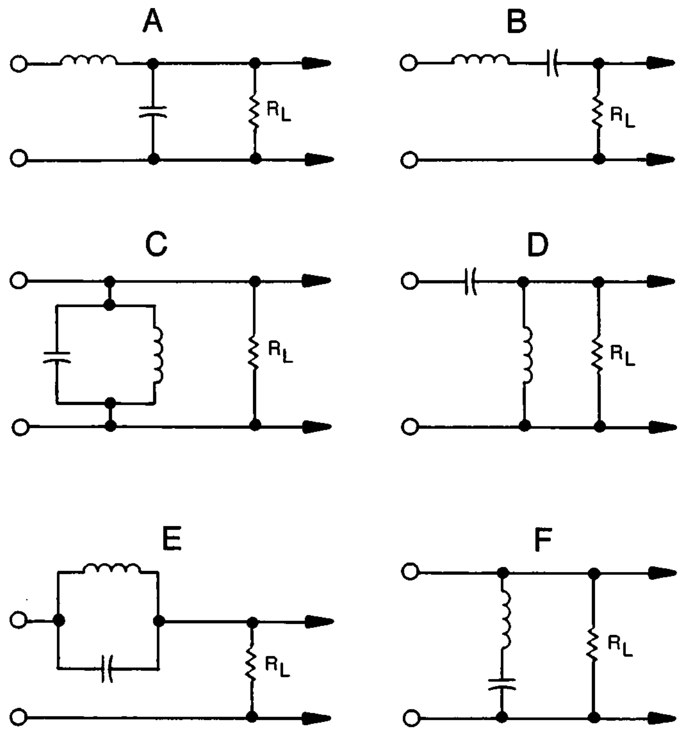


Figure 5-37

EXPERIMENT 9

LC Filters

OBJECTIVES: *To identify the frequency response of band-pass, band-stop, high-pass, and low-pass filters.*

To graph the frequency response curves for these AC filters.

To construct series, parallel, and combinational series-parallel filter networks.

To verify the cut-off frequencies, by comparing measured results with calculated values.

Introduction

In this experiment, you will construct six basic types of filters and plot a response curve for each one. Remember that the output voltage for the Trainer is not constant for the entire range of output frequencies. For this reason, your frequency response curves will not necessarily be exactly like the ones shown in the text.

Material Required

Heathkit Analog Trainer
Oscilloscope
AC Voltmeter
1 — 107 mH choke (#45-610)
1 — .01 μF capacitor
2 — 4700 Ω, 1/2-watt resistors (yellow-violet-red)
1 — 1000 Ω, 1/2-watt resistor (brown-black-red)
1 — 10 kΩ, 1/2-watt resistor (brown-black-orange)

Procedure

1. Construct the circuit shown in Figure 5-38.

2. Set the generator range switch to the high position.

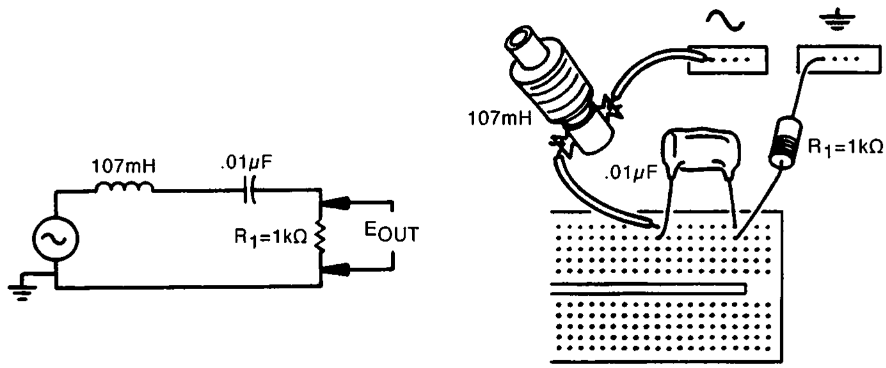


Figure 5-38
Circuit for step 1.

3. Refer to Figure 5-39. This diagram shows a typical response curve for the circuit you built in step 1. The curve was constructed by measuring E_{out} at several frequencies.

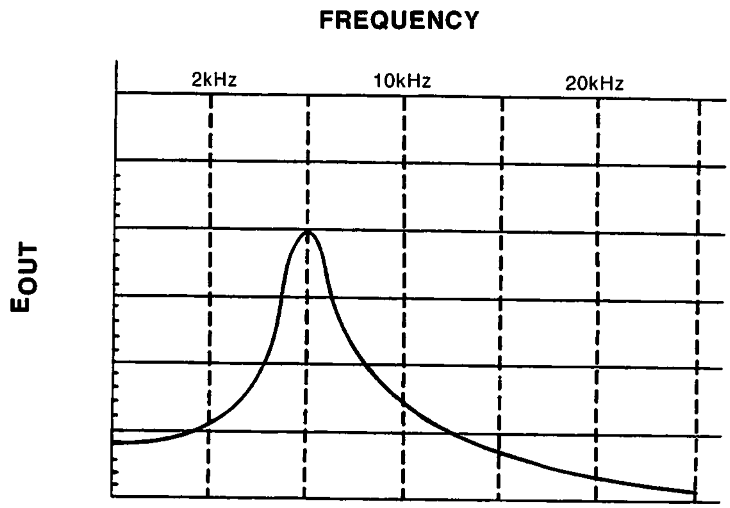


Figure 5-39
Plot the response curve for the circuit shown in Figure 5-38.

4. Connect your voltmeter across R. Set the generator frequency control fully counterclockwise. Measure the voltage across R. The voltage is __________ VAC.

5. Slowly rotate the frequency control clockwise to the 2 kHz position. The voltage across the resistor is:

$$E_{OUT} = \_\_\_\_\_\_\_\_\_\_ \text{ VAC}$$

6. Continue to turn the frequency control clockwise. Measure the voltage at each of the marked points on the frequency dial and at several points in between. Try to plot at least 20 different points across the frequency range. Record these voltages on a separate piece of paper, in order of increasing frequency.

7. Refer to Figure 5-39. Establish a scale for E_{out}, on the left-hand graph that ensures you can plot your maximum and minimum voltage values. Plot all of your voltage measurements, including those you measured in steps 4 and 5, on the graph.

8. Connect the points with a continuous line. Does your curve agree with the one originally shown in Figure 5-39? __________ .

9. Examine the circuit and the response curve. Determine the type of filter. The coil and capacitor form a __________ filter.

10. Disconnect the previous circuit and construct the circuit shown in Figure 5-40.

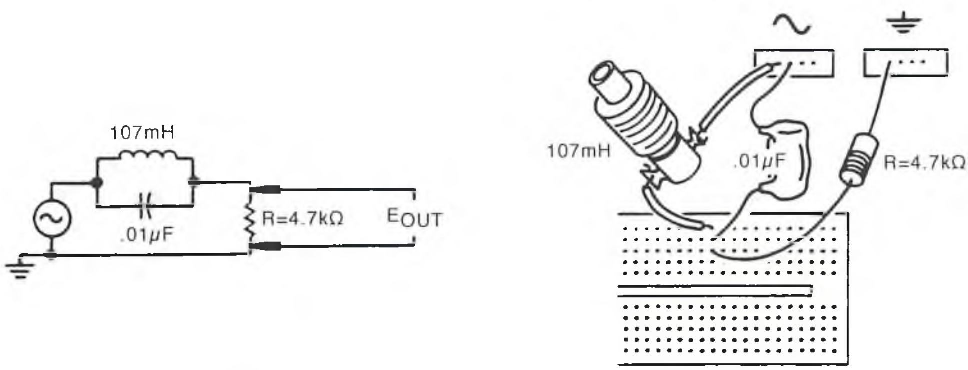


Figure 5-40
Circuit for step 10.

11. Connect the voltmeter across R. Using the procedure outlined in steps 4 through 8, plot the response curve for this circuit. Use the graph shown in Figure 5-41 to plot the curve.

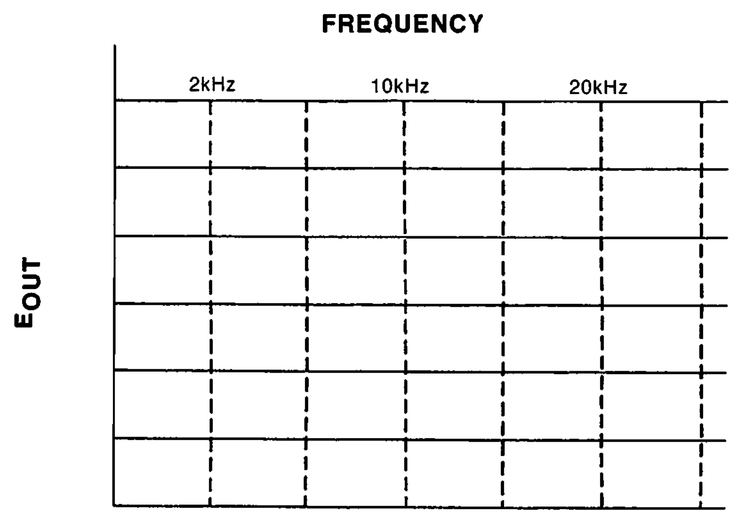


Figure 5-41
Plot the response curve for the circuit shown in Figure 5-40.

12. Examine the circuit and its response curve. Determine the type of filter. The capacitor and the coil form a ___________ filter.

13. Disconnect the previous circuit and construct the circuit shown in Figure 5-42.

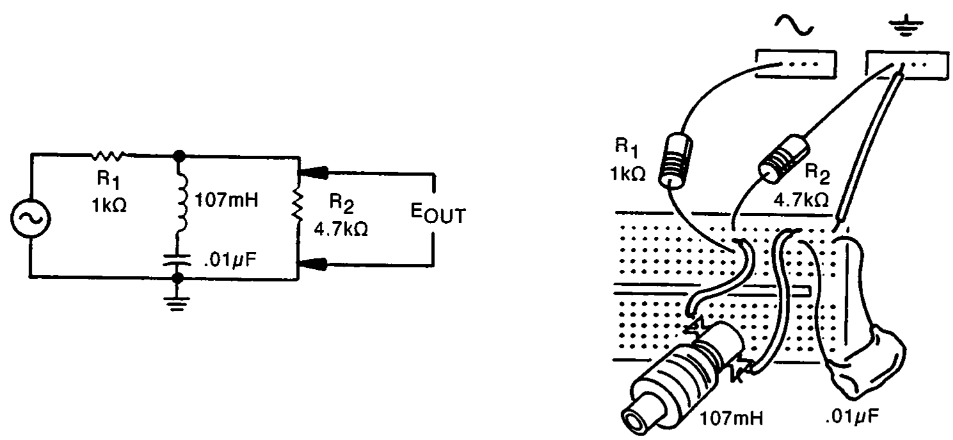


Figure 5-42
Circuit for step 13.

14. Connect the voltmeter across R_2 (not R_1). Use the above procedure to plot the response curve for this circuit on the graph in Figure 5-43.

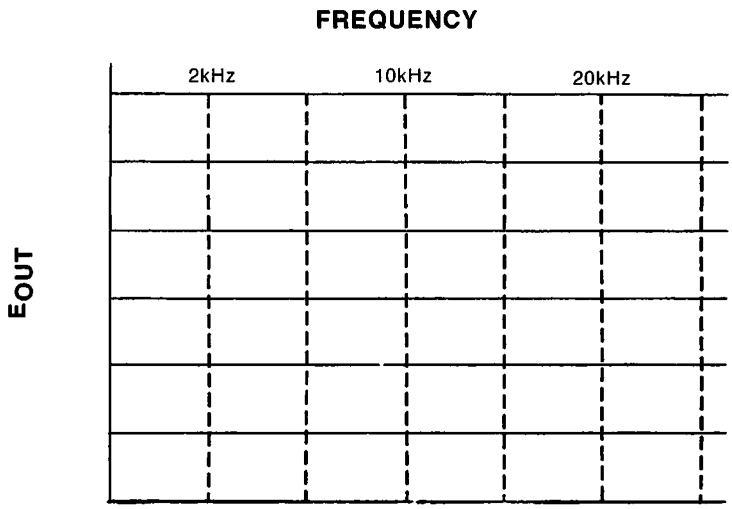


Figure 5-43
Plot the response curve of the circuit shown in Figure 5-42.

15. Examine the circuit and its response curve. Determine the type of filter. The capacitor and the coil form a __________ filter.

16. Disconnect the previous circuit and construct the circuit shown in Figure 5-44.

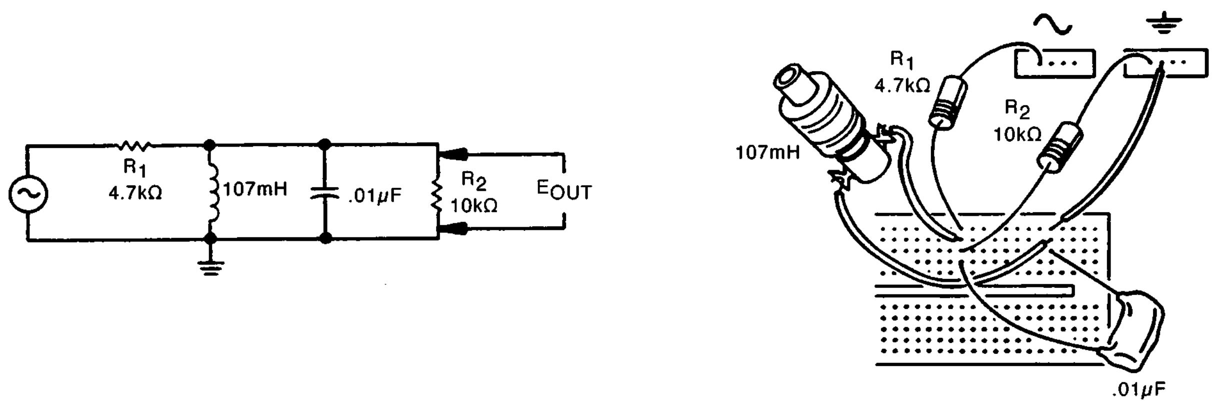


Figure 5-44
Circuit for step 16.

17. Connect the voltmeter across R_2 (not R_1). Use the above procedure to plot the response curve for this circuit on the graph in Figure 5-45.

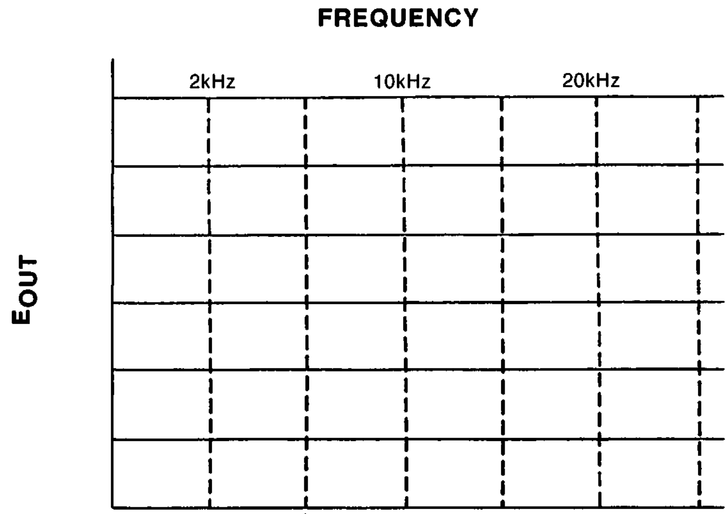


Figure 5-45
Plot the response curve of the circuit shown in Figure 5-44.

18. Examine the circuit and its response curve. Determine the type of filter. The capacitor and the coil form a __________ filter.

19. Disconnect the previous circuit and construct the circuit shown in Figure 5-46.

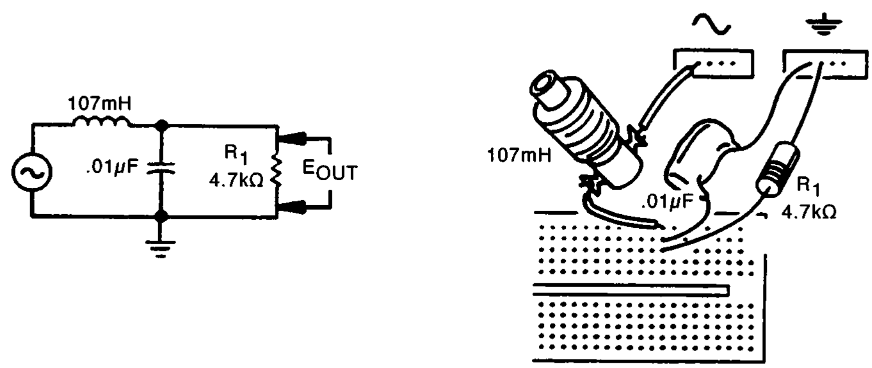


Figure 5-46
Circuit for step 19.

20. Connect the voltmeter across R. Use the above procedure to plot the response curve for this circuit on the graph in Figure 5-47.

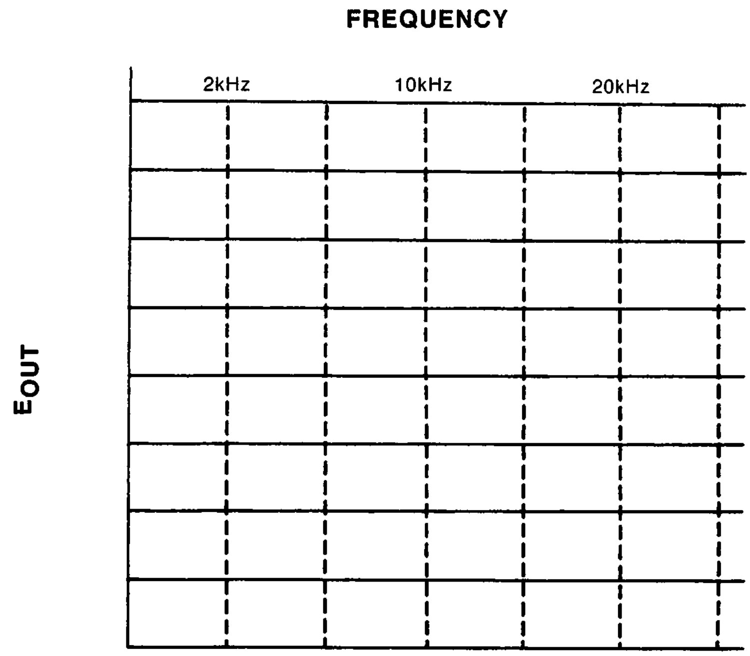


Figure 5-47
Plot the response curve for the circuit shown in Figure 5-46.

21. Examine the circuit and its response curve. Determine the type of filter. The capacitor and the coil form a ___________ filter.

22. Disconnect the previous circuit and construct the circuit shown in Figure 5-48.

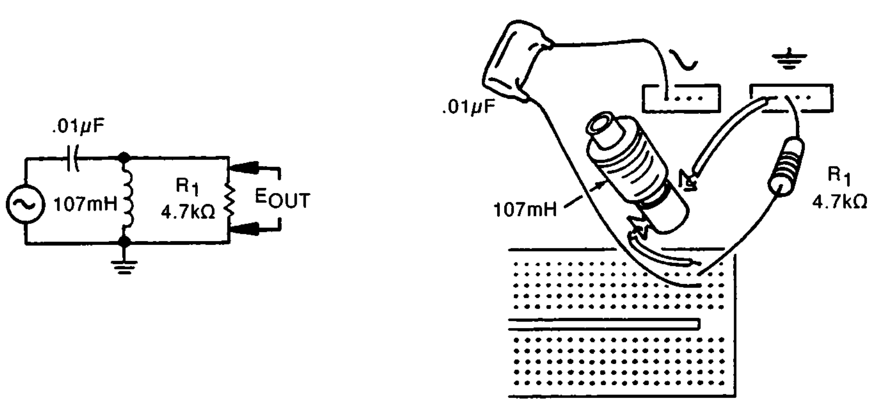


Figure 5-48
Circuit for step 22.

23. Connect the voltmeter across R. Use the above procedure to plot the response curve for this circuit on the graph in Figure 5-49 to plot the curve.

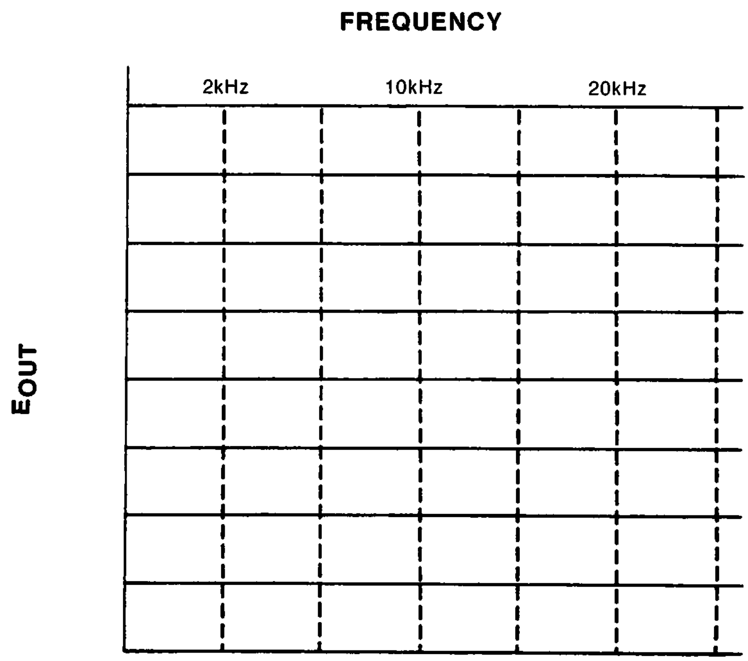


Figure 5-49
Plot the response curve of the circuit shown in Figure 5-48.

24. Examine the circuit and its response curve. Determine the type of filter. The capacitor and the coil form a __________ filter.

25. Turn the Trainer off and remove the circuit components from the Trainer.

Discussion

In step 1 you constructed the circuit shown in Figure 5-38. A typical response curve for this circuit was shown in Figure 5-39. In steps 4 through 8 you plotted your own response curve for the circuit. The general shape of your curve should agree with the typical curve. From the circuit arrangement and the response curve, it is obvious that this is a band-pass filter.

In step 10 you assembled the circuit shown in Figure 5-40. Next, you plotted a response curve for the circuit. A typical curve is shown in Figure 5-50. The general shape of your curve should agree with this curve. The circuit arrangement and the response curve tell us that this is a band-stop filter.

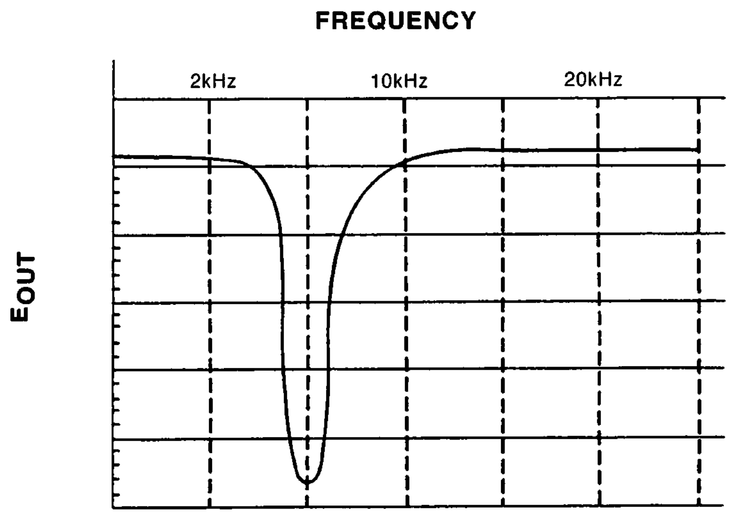


Figure 5-50
Typical response curve for the circuit
shown in Figure 5-40.

Next, you constructed the circuit shown in Figure 5-42 and plotted its response curve. The curve you plotted in Figure 5-43 should agree with the typical curve shown in Figure 5-51. This is the response curve of a band-stop filter.

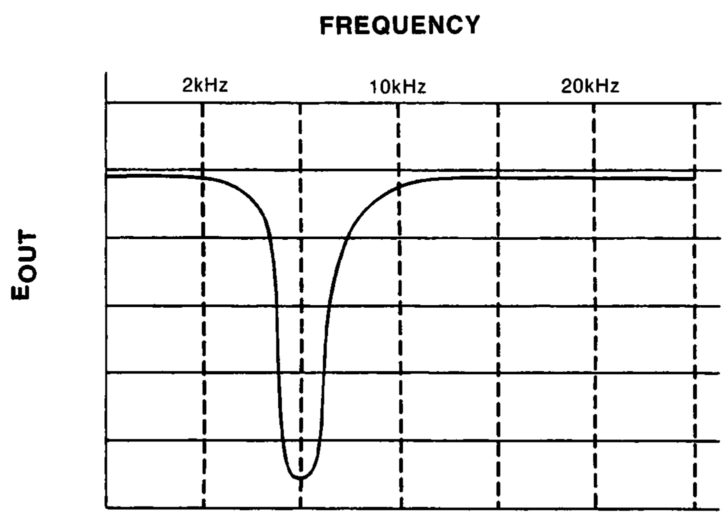


Figure 5-51
Typical response curve for the circuit
shown in Figure 5-42.

In step 16 you assembled the circuit shown in Figure 5-44 and plotted its response curve in Figure 5-45. A typical response curve is shown in Figure 5-52. Your curve should be similar. You will recognize that this is the response curve of a band-pass filter.

Next you built the circuit shown in Figure 5-46. A typical response curve is shown in Figure 5-53. Your curve should be similar. Because the high frequencies are blocked, this is a low-pass filter.

Finally you constructed the circuit shown in Figure 5-48. A typical response curve is shown in Figure 5-54. The curve indicates that this is a high-pass filter.

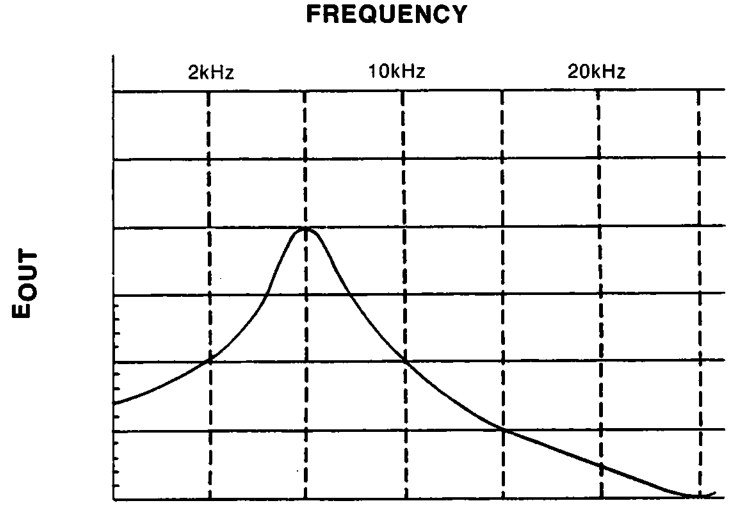


Figure 5-52
Typical response curve for the circuit shown in Figure 5-44.

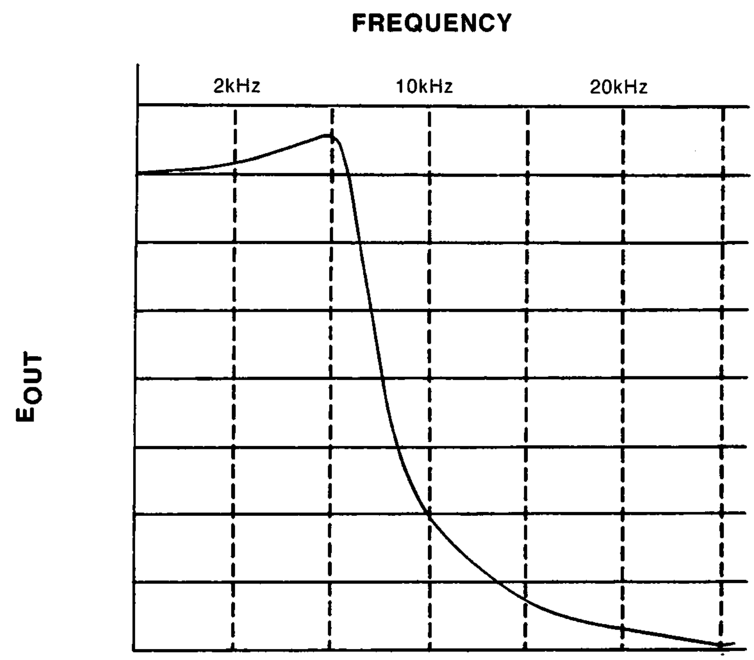


Figure 5-53
Typical response curve for the circuit shown in Figure 5-46.

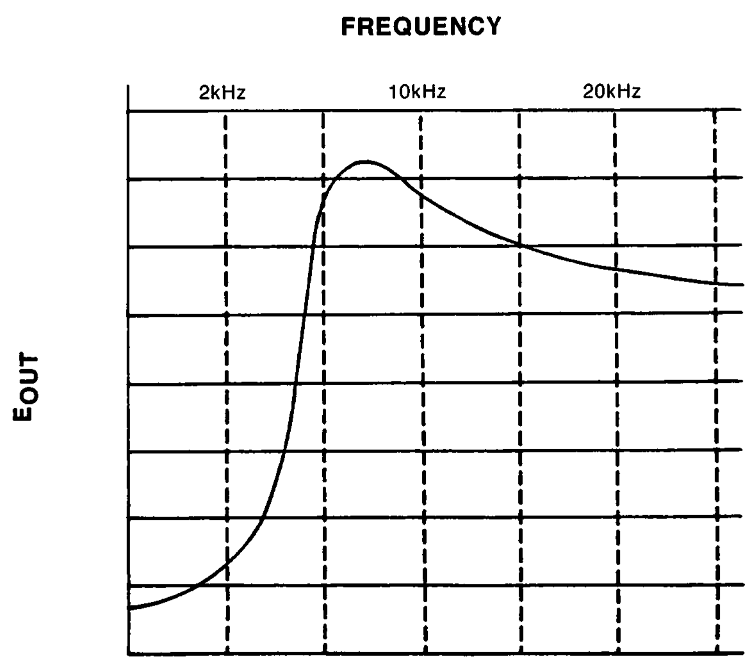


Figure 5-54
Typical response curve for the circuit shown in Figure 5-48.

SUMMARY

In a series RLC circuit, you find the total impedance with the formula:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Or, if X_C is larger than X_L, the formula becomes:

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

With parallel RLC circuits, it is easier to work with currents. The formula to find the total current is:

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$$

Or, if I_C is larger than I_L, the formula is:

$$I_T = \sqrt{I_R^2 + (I_C - I_L)^2}$$

SERIES-RESONANT CIRCUIT	PARALLEL-RESONANT CIRCUIT
Current maximum at resonance.	Line current minimum at resonance.
Impedance minimum at resonance.	Impedance maximum at resonance.
$Q = \frac{X_L}{R}$, $Q = \frac{E_C}{E_{in}}$, $Q = \frac{E_L}{E_{in}}$	$Q = \frac{X_L}{R}$, $Q = \frac{Z_{TANK}}{X_L}$, $Q = \frac{I_{TANK}}{I_{SOURCE}}$
Acts purely resistive at f_O.	Acts purely resistive at f_O.
At resonance, the source current and voltage are in phase.	At resonance, the source current and voltage are in phase.
Below resonance, the circuit acts capacitively.	Below resonance, the circuit acts inductively.
Above resonance, the circuit acts inductively.	Above resonance, the circuit acts capacitively.

Figure 5-55
Comparison of series and parallel resonant circuits.

For any LC circuit, there is a frequency at which X_L is equal to X_C. This frequency is called the resonant frequency, f_O. You can determine the resonant frequency with the formula:

$$f_O = \frac{.159}{\sqrt{LC}}$$

Some of the characteristics of a series-resonant circuit are quite different from those of a parallel resonant circuit. The table in Figure 5-55 summarizes the differences and the similarities. The conditions described are generally true for high-Q resonant circuits.

One practical application of tuned circuits is the filter. Figure 5-56 summarizes the six basic types of filters that were described in this unit.

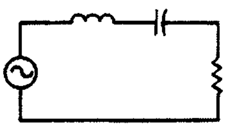
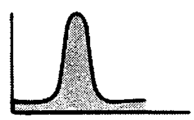
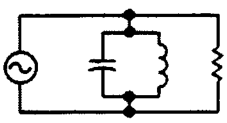
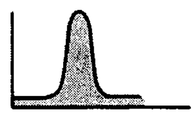
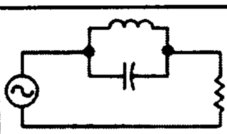
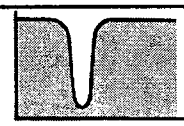
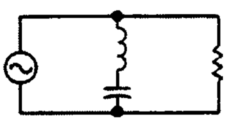
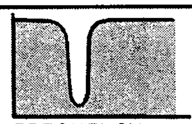
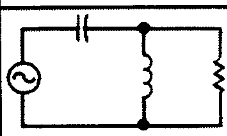
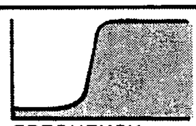
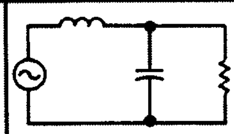
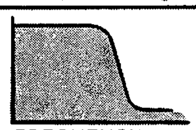
TYPE	TYPICAL CIRCUIT	RESPONSE CURVE	COMMENTS
BAND-PASS		 FREQUENCY →	PASSES A BAND OF FREQUENCIES AROUND F_O.
BAND-PASS		 FREQUENCY →	PASSES A BAND OF FREQUENCIES AROUND F_O.
BAND-STOP		 FREQUENCY →	BLOCKS OR ATTENUATES A BAND OF FREQUENCIES AROUND F_O.
BAND-STOP		 FREQUENCY →	BLOCKS OR ATTENUATES A BAND OF FREQUENCIES AROUND F_O.
HIGH-PASS		 FREQUENCY →	BLOCKS OR ATTENUATES FREQUENCIES BELOW A CERTAIN CUTOFF FREQUENCY.
LOW-PASS		 FREQUENCY →	BLOCKS OR ATTENUATES FREQUENCIES ABOVE A CERTAIN CUTOFF FREQUENCY.

Figure 5-56

Comparison of filter types.

APPENDIX A. RESONANCE NOMOGRAPH

Figure A-1 is a nomograph which you can use to solve resonance problems. The accuracy of this graph is about 5% for most problems. You can use it to solve three types of resonance problems.

It helps you determine the resonant frequency of a series- or parallel-resonant circuit when you know the inductance and capacitance values. For example, if a 100 mH coil is connected in series with a .022 μF capacitor, what is the resonant frequency? First draw a straight line from 0.022 μF in the left column to 100 mH in the right column. Now read the resonant frequency from the center column. Figure A-1 indicates a resonant frequency of about 3.4 kHz. The exact value should be 3.383 kHz. As you can see, the graph was fairly accurate.

You can also use the graph to determine the inductance when you know the capacitance and resonant frequency. For example, what value of inductance is required to resonant at 3.4 kHz when it connected in parallel with a .022 μF capacitor? Draw a straight line is drawn from 0.22 μF on the left column through 3.4 kHz in the center column. Then read the inductance from the point at which this line crosses the right column.

Finally, you can use the graph to find the capacitance when you know the resonant frequency and the inductance. Draw a straight line from the two known quantities. Then read the capacitance from the point at which this line crosses the left column.

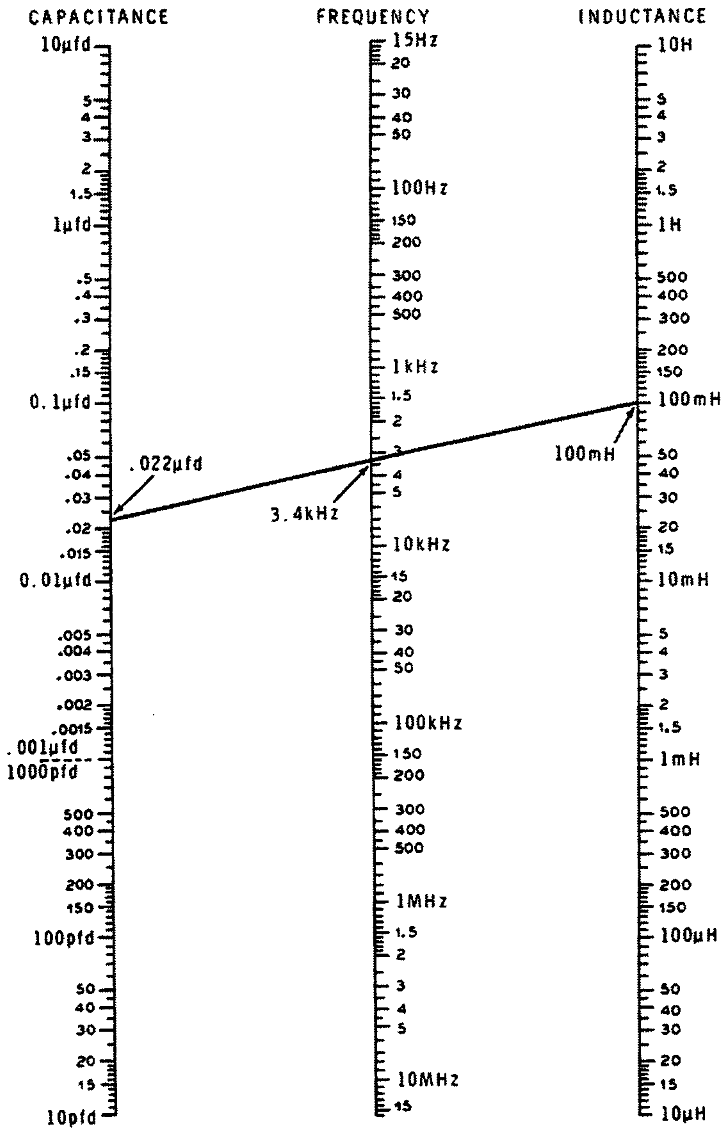


Figure A-1
Resonance Nomograph.

UNIT EXAMINATION

The following multiple choice examination is designed to test your understanding of the material that was presented in this unit. Place a check beside the multiple choice answer (A, B, C, or D) that you feel is most correct. After you complete the examination, compare your answers with the correct ones that appear after the exam.

1. What is the impedance of the circuit shown in Figure 5-57?

   A. 8.2 Ω
   B. 11.2 Ω
   C. 14.4 Ω
   D. 18.8 Ω

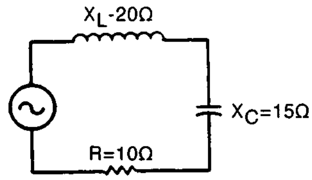


Figure 5-57
Circuit for question 1.

2. What is the impedance of the circuit shown in Figure 5-58?

   A. 8.9 Ω
   B. 5.5 Ω
   C. 1.225 Ω
   D. 1.5 Ω

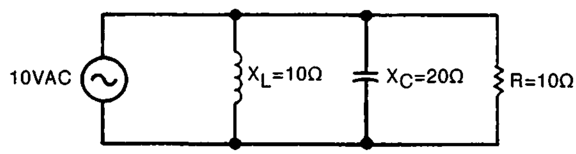


Figure 5-58
Circuit for question 2.

3. Which of the circuits shown in Figure 5-59 is at resonance?

   A. Figure 5-59A.
   B. Figure 5-59B.
   C. Figure 5-59C.
   D. Figure 5-59D.

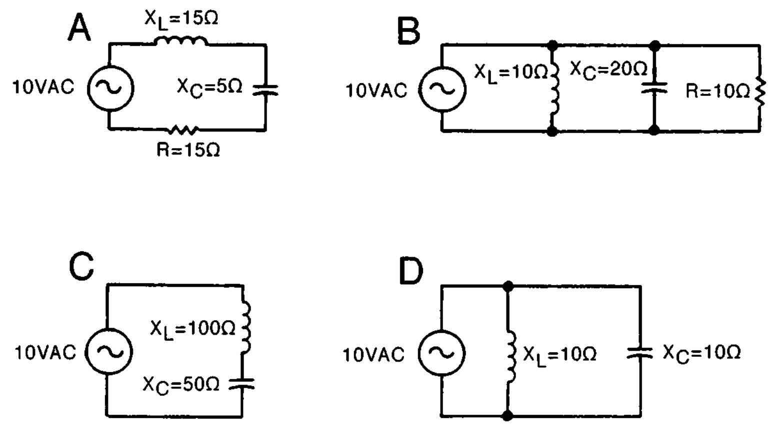


Figure 5-59
Circuit for question 3.

4. An 8-Henry choke is connected in series with a 2 μF capacitor. What is the resonant frequency?

   A. 126.5 Hz.
   B. 12.65 Hz.
   C. 40 Hz.
   D. 400 Hz.

5. Which of the following statements is true of a series-resonant circuit?

   A. Its impedance is maximum at resonance.
   B. The line current is maximum at resonance.
   C. The voltage across the capacitor is always less than the applied voltage.
   D. The Q is directly proportional to the series resistance.

6. Which of the following statements is true of a parallel-resonant circuit?

   A. At resonance, the circulating current within the tank is greater than the line current.
   B. At resonance, the line current is maximum.
   C. The voltage across the capacitor or coil may be higher than the applied voltage.
   D. At resonance, you can find the impedance of the tank with the formula: $Z = \frac{Q}{X_L}$.

7. A series circuit is resonant at 10 kHz and has a Q of 10. The band of frequencies to which the circuit responds is from:

   A. 1 kHz to 10 kHz.
   B. 10 kHz to 11 kHz.
   C. 9 kHz to 11 kHz.
   D. 9.5 kHz to 10.5 kHz.

8. What value capacitor must you connect across a 56 mH coil to resonate at 5000 Hz?

   A. 0.55 μF.
   B. 0.018 μF.
   C. 0.4 μF.
   D. 0.22 μF.

9. A variable capacitor has a minimum capacitance of 100 pF and a maximum value of 400 pF. When it is connected across a 100 μH coil, you can tune the tank circuit to resonate at frequencies between:

   A. 159 kHz to 795 kHz.
   B. 795 kHz to 3.18 MHz.
   C. 1.59 MHz to 3.18 MHz.
   D. 795 kHz to 1.59 MHz.

10. Refer to Figure 5-60. L_1 and C_1 have the same resonant frequency (f_O) as L_2 and C_2. This type of filter:

   A. blocks a band of frequencies around f_O.
   B. passes only the band of frequencies around f_O.
   C. blocks frequencies below f_O.
   D. blocks frequencies above f_O.

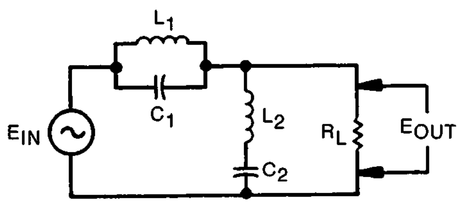


Figure 5-60
Circuit for question 10.

EXAMINATION ANSWERS

1 B— $Z = \sqrt{R^2 + (X_L - X_C)^2}$

$Z = \sqrt{10\ \Omega^2 + (20\ \Omega - 15\ \Omega)^2}$

$Z = \sqrt{100 + 25}$

$Z = \sqrt{125}$

$Z = 11.2\ \Omega$

2. A— The first step is to find the current in each leg of the circuit.

$$I_L = \frac{E}{X_L} = \frac{10\text{ VAC}}{10\ \Omega} = 1\text{ A}$$

$$I_C = \frac{E}{X_C} = \frac{10\text{ VAC}}{20\ \Omega} = 0.5\text{ A}$$

$$I_R = \frac{E}{R} = \frac{10\text{ VAC}}{10\ \Omega} = 1\text{ A}$$

Now, you can find the total current:

$$I_T = \sqrt{{I_R}^2 + (I_L - I_C)^2}$$

$$I_T = \sqrt{1\text{ A}^2 + (1\text{ A} - 0.5\text{ A})^2}$$

$$I_T = \sqrt{1^2 + 0.5^2}$$

$$I_T = \sqrt{1 + 0.25}$$

$$I_T = \sqrt{1.25}$$

$$I_T = 1.12\text{ A}$$

Now, you can find the impedance:

$$Z = \frac{E}{I_T}$$

$$Z = \frac{10\ \text{VAC}}{1.12\ \text{A}}$$

$$Z = 8.9\ \Omega$$

3. D— This is the only circuit in which X_L equals X_C.

4. C— $$f_O = \frac{.159}{\sqrt{LC}}$$

$$f_O = \frac{.159}{\sqrt{8\ \text{H} \times 0.000\ 002\ \mu\text{F}}}$$

$$f_O = \frac{.159}{\sqrt{0.000\ 016}}$$

$$f_O = \frac{.159}{0.004}$$

f_O = 39.75 Hz or about 40 Hz

5. B— At resonance, the line current is maximum.

6. A— At resonance, the circulating current is greater than the line current.

7. D— The bandwidth is:

$$BW = \frac{f_O}{Q} = \frac{10\ \text{kHz}}{10} = 1\ \text{kHz}$$

The center of this band is 10 kHz. Thus, the band must extend from 9.5 kHz to 10.5 kHz.

8. B— $C = \frac{1}{4\pi^2 f^2 L}$

$$C = \frac{1}{39.4\ (5000)^2\ 0.056}$$

$$C = \frac{1}{39.4\ 25{,}000{,}000)(0.056)}$$

$$C = \frac{1}{55{,}160{,}000}$$

$$C = 0.018\ \mu F$$

9. D— Determine the minimum frequency:

$$f_o = \frac{.159}{\sqrt{LC}}$$

$$f_o = \frac{.159}{\sqrt{.0001\ H \times .000\ 000\ 0004\ \mu F}}$$

$$f_o = \frac{.159}{\sqrt{.000\ 000\ 000\ 000\ 04}}$$

$$f_o = \frac{.159}{.0000002}$$

$$f_o = 795\ kHz$$

Determine the maximum frequency:

$$f_o = \frac{.159}{\sqrt{LC}}$$

$$f_o = \frac{.159}{\sqrt{.0001\ H \times .000\ 000\ 000\ 1\ \mu F}}$$

$$f_o = \frac{.159}{.0000001}$$

$$f_o = 1.59\ MHz$$

10. A— L_1 and C_1 form a parallel-resonant band-stop filter. L_2 and C_2 form a series-resonant band-stop filter. Both filters tend to attenuate or block a band of frequencies around F_O.

APPENDIX B: THE j OPERATOR

Alternating current is easier to understand when you use graphics to demonstrate phase relationships and variations in amplitude. An oscilloscope provides a visual representation of measured voltage. To understand complex AC circuits, you must be able visualize alternating current.

The characteristics of a sine wave continuously change through three hundred and sixty degrees of rotation. With a graphic representation called a *vector* plot, you can show these changes in both magnitude and direction. That's because every point on a sine wave has a component of magnitude and direction. The vector is a method that represents those quantities.

You have been using vectors throughout the AC course. As you learned, they are quite useful for illustrating certain characteristics of AC circuits. This appendix has been written as a supplement to the vector theory that was already presented. It will show you how to combine many common values, such as individual impedances, to determine the total circuit impedance. While you will also use vector plots to show basic concepts in this presentation, the main purpose of this appendix is to show you how to express vectors mathematically.

When you express vectors mathematically, you must use a *complex number.* A complex number (r) is the sum of a real number (a) and an imaginary number (jb). It is usually written in the form r = a + jb. A *real number* is any of the rational or irrational numbers. An imaginary number is the product of a real number and an *imaginary unit* called the *j operator.* The j operator is a mathematical device that is equal to the square root of minus one ($\sqrt{-1}$).

You will learn in this appendix how you can use the j operator to simplify and represent the characteristics of AC circuits in both graphical and mathematical terms.

To begin, the j operator is identical to the i operator that is used as the common representation for imaginary units, or numbers, in pure mathematics. Because you can mistake the letter "i" for the term *instantaneous current,* electrical mathematics has adopted the letter "j" to represent the imaginary unit.

At this point you may be wondering, Where did the imaginary number come from? Although many great discoveries have occurred in science and technology in recent years, it is interesting to note that much of the pure math that is used to understand and prove these events has been around for hundreds of years! As a matter of fact, the math that involves an imaginary unit (i or j operator) was in place in the 1600 century. Imaginary numbers were suggested in 1572 by Raphael Bombelli, a mathematician. Applications for imaginary numbers, however, did not appear until several hundred years later.

The vector diagram in Figure B-1 graphically illustrates real and imaginary numbers. The real numbers are located on the horizontal axis, while the imaginary numbers are located on the vertical axis. Note that the vertical axis is designated the j axis. Don't let the word imaginary fool you, these j quantities are very real. You can use the j operator to specify all of the reactive component vectors mathematically, and then, compute their combined values algebraically. This procedure allows you to compute the complex number that is needed to represent the sum of all the resistive and reactive values in an AC circuit.

Now look at Figure B-1 again. Note that because it is a vector diagram, the axes identify the angles between 0° and 360°. Furthermore, the three electrical characteristics that determine impedance in an AC circuit and their relationship on the vector diagram, are also identified in the figure. The 0° vector is used to plot purely resistive values, the 90° vector is used to plot inductive reactance (X_L) values, and the 270° vector is used to plot capacitive reactance (X_C) values.

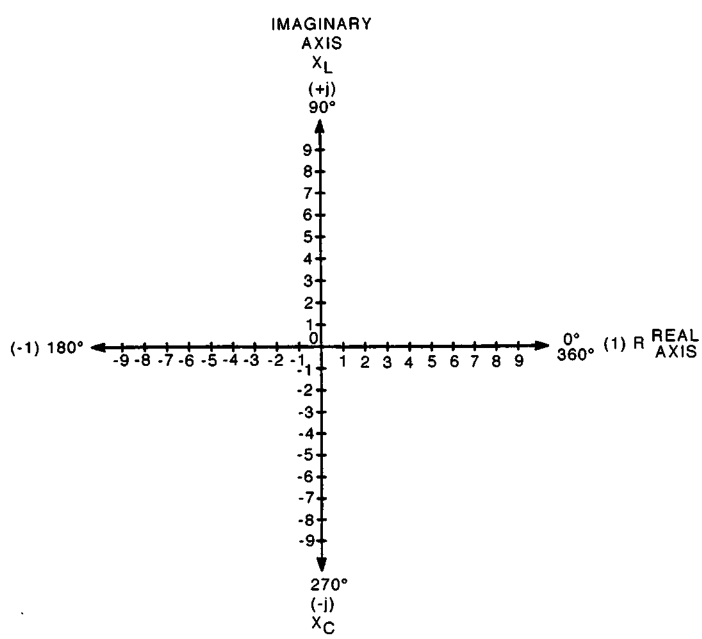


Figure B-1

One final point; when you write the imaginary number, you place the j operator in front of the real number. That's because the polarity of the j operator is used to indicate the *direction* of the vector and the number indicates the *magnitude* of the vector. As you can see in Figure B-1, the +j operator represents inductive reactance, X_L, and the j operator represents capacitive reactance Xc. Note that pure resistance is graphed on the horizontal axis because it is unaffected by changes in frequency, and is therefore, a reference for both X_L and X_C. When you graph impedance in this manner, the 180° phase relationship between inductive and capacitive circuits becomes obvious.

Now, just what can the j operator do for you? Specifically, it allows you to find the square root of a negative number. For example if $X^2 = -4$, you might say $X = \sqrt{-4}$. However, this is not defined as a real number. So, to find the square root of a negative number, you must use the imaginary unit, the j operator, to represent the imaginary number $\sqrt{-4}$. Since you know that $j = \sqrt{-1}$, and $\sqrt{-4} = \sqrt{-1}$, then $\sqrt{-4} = j2$.

There will be times when you will have to work with powers-of-j in an equation. Following is a list of powers-of-j to introduce you to the concept.

$j^0 = 1$ (a number raised to the 0 power equals 1)

$j^1 = \sqrt{-1} = +j$ (a number raised to the 1 power equals itself)

$j^2 = \sqrt{-1} \times \sqrt{-1} = -1$

$j^3 = j^2 \times j = -1 \times j = -j$

$j^4 = j^2 \times j^2 = -1 \times -1 = 1$

Note that after j^3, the values of the powers-of-j repeat. Furthermore, even numbered powers result in real numbers, while odd-numbered powers result in positive or negative imaginary units.

Once again, look at Figure B-1. Note that each vector represents a power of j. At 0°, it is j^0, or 1. At 90°, it is j^1, or +j. At 180°, it is j^2, or –1. At 270°, it is j^3, or j. And at 360°, it j^4, or 1, the same value as for 0°. You can also see that the horizontal axis contains real numbers, while the vertical axis contains imaginary numbers.

Now that you have a brief introduction to imaginary number and the j operator, take a look at some examples of how you could use j. Figure B-2 shows how a vector quantity of 5 ohms could be graphically represented. Part A shows pure resistance (R), Part B shows inductive reactance (X_L), and Part C shows capacitive reactance (X_C).

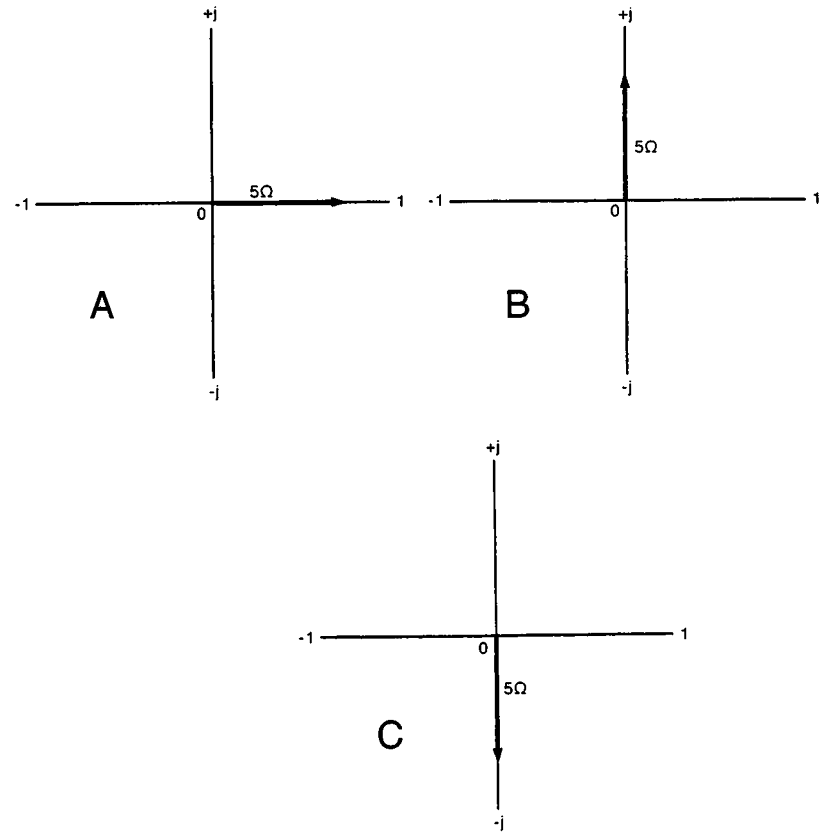


Figure B-2

If you had a series circuit that combined 3 ohms of inductive reactance (X_L) and 4 ohms of pure resistance (R), the total circuit impedance (Z_T) equals the complex number 4 + j3. To arrive at this, plot the resistance and reactance values as vectors. You plot resistance on the positive "real" axis, and you plot inductive reactance on the positive "imaginary" (+j) axis.

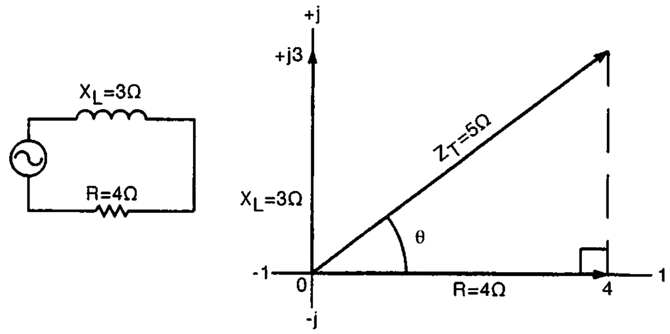


Figure B-3

The circuit diagram and vector plot are shown in Figure B-3, and the equivalent mathematical computations follow. Note that the vector for total impedance is the hypotenuse of a right triangle that is formed by the resistance and inductive reactance vectors. Therefore, you are able to use Pythagorean's Theorem to solve for total impedance.

$$Z_T = \sqrt{R^2 + X_L{}^2}$$

$$Z_T = \sqrt{4^2 + 3^2}$$

$$Z_T = \sqrt{16 + 9}$$

$$Z_T = \sqrt{25}$$

$$Z_T = 5\ \Omega$$

The direction the total impedance vector points is identified by angle Theta (θ). This angle represents the current versus voltage *phase angle* of the circuit. You use a trigonometric function, normally, the tangent of Theta, to calculate it.

$$\tan\theta = \frac{OPP}{ADJ}$$

Transposing the equation to solve for Theta, we get:

$$\theta = \arctan\frac{OPP}{ADJ}$$

$$\theta = \arctan\frac{3}{4}$$

$$\theta = \arctan 0.75$$

$$\theta = 36.8699°$$

You can see from this simple example that you can calculate the total impedance and phase angle for a series circuit with two out-of-phase impedances. You also found that you can accomplish the same thing with a vector plot and complex numbers.

Now look at conditions where there are more than two out-of-phase impedances in a series circuit. You will see that the j operator can be a real work saver in your evaluation. For example, examine a combinational series RLC circuit. Figure B-4 shows the schematic diagram, and three vector plots for such a circuit. Plot A shows the individual circuit impedances.

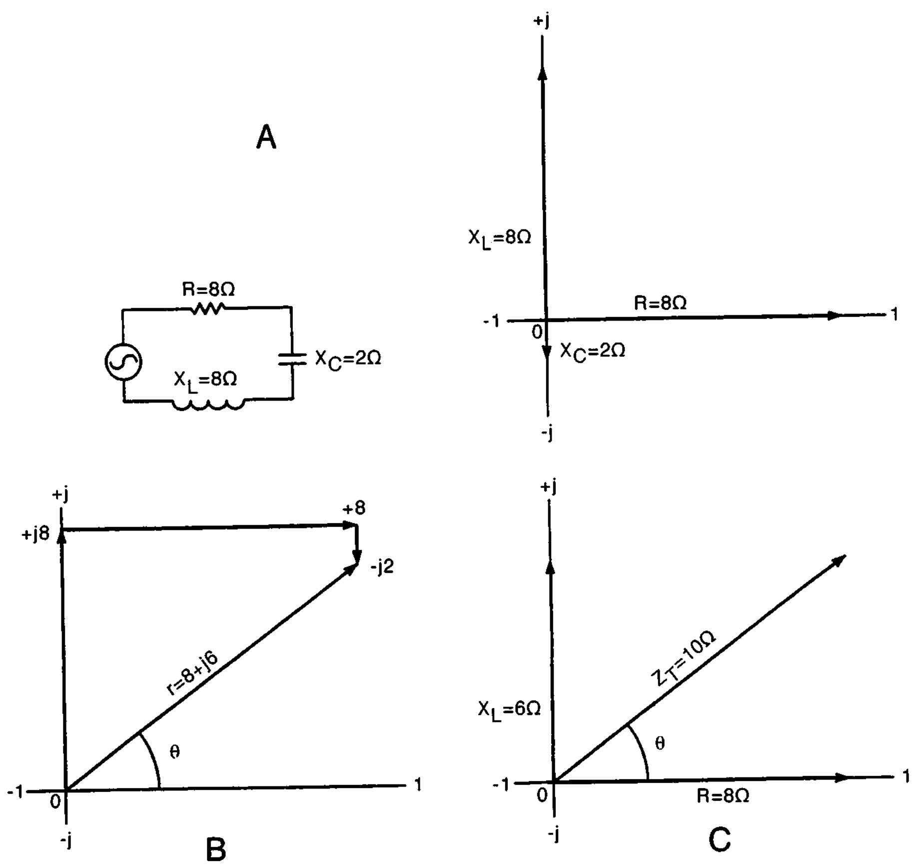


Figure B-4

Plot B shows how you can add the individual vectors to determine the sum. Use this process to draw the vectors:

1. Select a vector (any one of the impedance vectors) and plot it as usual, with its tail at the origin of the horizontal and vertical axes. This example uses the vector for X_L. Eight ohms of inductive reactance has been plotted on the positive imaginary axis. Therefore, it is equal to the imaginary number +j8.

2. Next, place the tail of another vector at the tip of the first—this example uses the vector for R. Eight ohms of pure resistance is plotted in the direction of the positive real axis. Therefore, it is equal to the real number 8.

3. Continue to connect vectors, tail-to-tip, until you have them all plotted. You have one left, the vector for X_C. Plot two ohms of capacitive reactance in the direction of the negative imaginary axis. Therefore, it is equal to the imaginary number j2.

4. Finally, connect the tip of the last vector back to the origin of the axes. This line represents the sum (Z_T) of the individual impedances.

Plot C in Figure B-4, is the result of mathematically combining the three real and imaginary numbers into a complex number. You accomplish this by assigning the appropriate j operator to each component value and adding the values:

$$r = 8 + j8 - j2$$

$$r = 8 + j6$$

In the equation (and in plot B) "r" is the ***result,*** or sum, of the real and imaginary numbers, or vectors. Each value on the right side of the equation represents a real or an imaginary number that is also represented as a vector in plot B. In the equation, the resistor value doesn't get a j operator because it is a real number. The inductor value gets a +j operator, while the capacitor gets a j operator.

The final complex number contains only two values. The first, the real number, defines the real number vector. The second, the imaginary number, defines the imaginary vector and the direction that it is plotted—in this case, on the positive imaginary number axis.

Now that you've established the value for the opposite and adjacent sides of the right triangle formed by the vectors +j6 and 8, you can use Pythagorean's Theorem to calculate the total impedance of the circuit. Simply use the real number for the resistance value in the equation, and use the imaginary number, without the j operator, for the reactance value in the equation. Therefore:

$$Z_T = \sqrt{R^2 + X_L{}^2}$$

$$Z_T = \sqrt{8^2 + 6^2}$$

$$Z_T = \sqrt{64 + 36}$$

$$Z_T = \sqrt{100}$$

$$Z_T = 10\ \Omega$$

Note that this equation used the term X_L to represent the circuit reactance. That's because the value is a positive imaginary number, which indicates the circuit reactance is primarily inductive reactance.

Since you calculated the complex number that represents the impedance vector of the circuit, you can also calculate the angle Theta. Note that the value for the side opposite the angle is the imaginary number without the j operator, while the value for the side adjacent to the angle is the real number.

$$\theta = \arctan \frac{OPP}{ADJ}$$

$$\theta = \arctan \frac{6}{8}$$

$$\theta = \arctan 0.75$$

$$\theta = 36.8699°$$

When you begin to work with circuits that have several individual resistances and reactances, it becomes impractical to plot each of the impedance vectors to determine total impedance. That's where the j operator comes into its own. Look at the circuit in Figure B-5. It contains six components that can affect the total impedance of the circuit. Mathematically, this is how you simplify the vectors — assign the appropriate j operator to each reactance value; then, add the resistances and reactances as you did earlier. Again, the idea is the reduce the equation to one real number and one imaginary number. To do this, add the similar components as follows:

$$r = j210 + 20 - j50 + j100 + 10 - j300$$

$$r = 30 + j310 - j350$$

$$r = 30 - j40$$

This tells you the sum of the vectors is equal to a positive real number 30 (resistance) and a negative imaginary number 40 (reactance). The vector plot is also shown in Figure B-5.

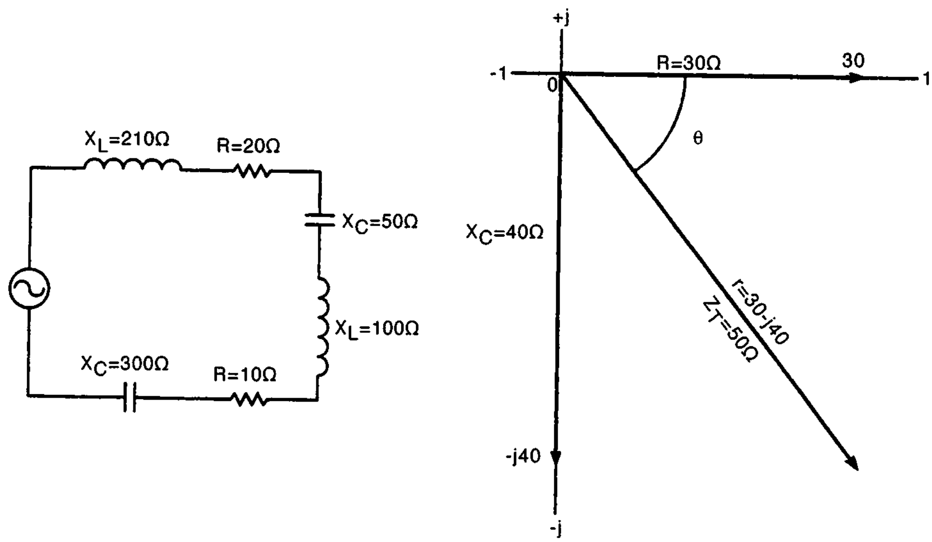


Figure B-5

Now that the circuit values have been reduced to two terms, you can easily calculate total impedance. Use the real number for the resistive term, and the imaginary number, without the j operator, for the reactive term. Note that this example uses X_C in the equation because the j operator was a negative value.

$$Z_T = \sqrt{R^2 + X_C{}^2}$$

$$Z_T = \sqrt{30^2 + 40^2}$$

$$Z_T = \sqrt{900 + 1600}$$

$$Z_T = 2500$$

$$Z_T = 50\ \Omega$$

You can also use the impedance vector values to calculate the phase angle Theta. As before, the real number is the side adjacent to the angle, while the imaginary number, without the j operator, is the side opposite the angle.

$$\theta = \arctan \frac{OPP}{ADJ}$$

$$\theta = \arctan \frac{40}{30}$$

$$\theta = \arctan 1.33$$

$$\theta = 53.13°$$

The phase angle is 53.13°. But, note in Figure B-5 that the angle is below the horizontal axis. This reinforces the fact that there is more capacitive reactance in the circuit than inductive reactance.

Although the examples used impedance calculations, you can just as easily substitute voltage or current in each calculation and vector. Just remember, do not mix the quantities. If you wish, for example, to determine the vector for total voltage, make sure the individual component vectors represent voltage. To see what this means, look at Figure B-6. It shows a series circuit with five components. The impedance for each component is specified, along with the voltage drop across each component. You will use the voltage drops to determine source voltage.

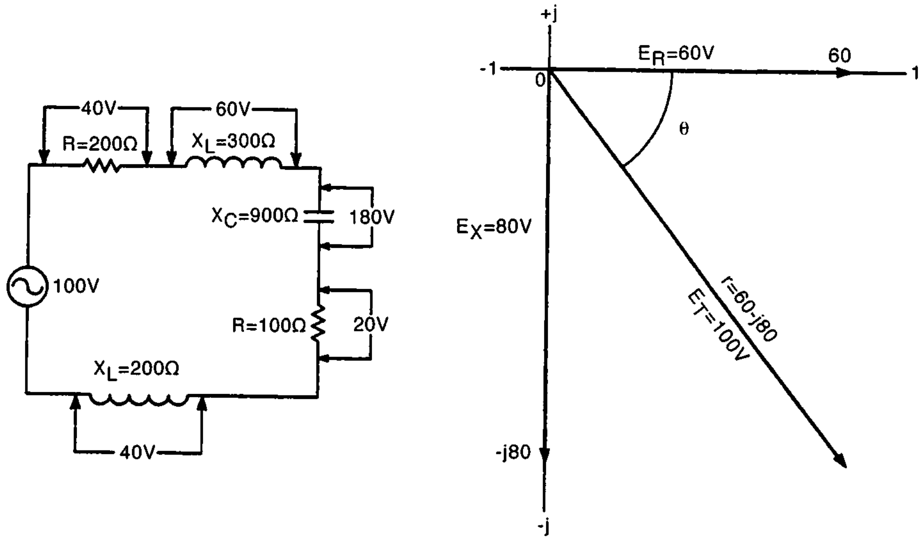


Figure B-6

If you simply add the voltage drops, like you would in a purely resistive circuit, you will wind-up with a total circuit voltage drop of 340 volts. But, you know that can't bc true, since the schematic already specifies a source voltage rise of 100 volts. Why the big difference? By now you should realize that like inductive and capacitive reactances, their vollages also oppose each other. Therefore, you must use the j operator when you total the voltage drops in an AC circuit. Use the voltage drops in Figure B-6 to review the process.

Recall that the first step is to use the j operator to reduce the circuit values to one real and one imaginary number. That is, calculate the sum of the vectors.

$$r = 40 + j60 - j180 + 20 + j40$$

$$r = 60 + j100 - j180$$

$$r = 60 - j80$$

Next, use the elements of the resulting complex number and Pythagorean's Theorem to calculate source voltage.

$$E_T = \sqrt{E_R^{\,2} + E_X^{\,2}}$$

$$E_T = \sqrt{60^2 + 80^2}$$

$$E_T = \sqrt{3600 + 6400}$$

$$E_T = \sqrt{10000}$$

$$E_T = 100\ \text{V}$$

Thus, you find the source voltage is, indeed, 100 volts.

To find the current through an AC series circuit, you simply divide the voltage drop across a component by its impedance. If you don't know the voltage drop, calculate total impedance; then, divide source voltage by total impedance.

You should note that the procedure you use for the j operator and to plot vectors for **parallel** AC circuits is similar to the way you plot vectors for **series** AC circuits. While the procedures are comparable, there is one major difference, the vertical axis (j operator) quantities are interchanged. That is, the complex number which represents the capacitive quantity (current or reactance) uses the +j operator, and the complex number which represents the inductive quantity uses the j operator.

To make sure you understand the process, consider the parallel AC circuit in Figure B-7. To find the total current, first use the j operator to sum the individual currents:

$$r = 2 - j0.5 + j1 + 2 - j0.5 + j3$$

$$r = 4 - j1 + j4$$

$$r = 4 + j3$$

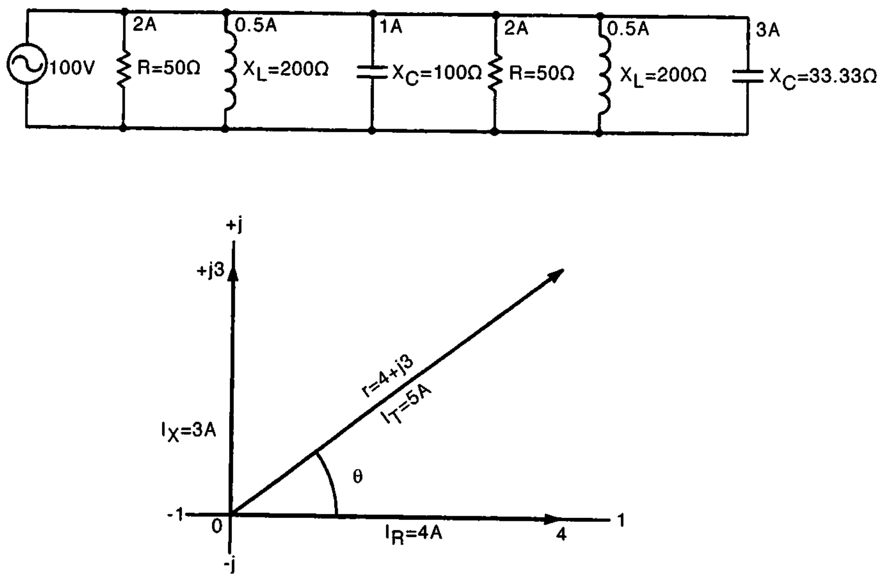


Figure B-7

The vector plot for the total current is also shown in Figure B-7. (To verify the accuracy of the calculations, you may wish to plot the individual vectors, "tail to-tip," as you learned earlier.)

Now that you know the sum of the current vectors, you can calculate total cur rent using Pythagorean's Theorem, just like you did for total voltage in a series circuit.

$$I_T = \sqrt{I_R^2 + I_X^2}$$

$$I_T = \sqrt{4^2 + 3^2}$$

$$I_T = \sqrt{16 + 9}$$

$$I_T = \sqrt{25}$$

$$I_T = 5\text{ A}$$

Since you now know the source voltage and total current, you can use Ohm's Law to calculate total impedance. On the other hand, what do you do if you don't know the total current? You apply the j operator and calculate the sum of the impedance vectors. However, you must keep in mind that the total impedance of a parallel circuit is always less than the individual parallel resistances or reactances. For that reason, it is not possible to plot the impedance vectors, or mathematically employ the j operator, unless you use the reciprocal values for the impedances, as follows.

$$\frac{1}{r} = \frac{1}{50} - \frac{1}{j200} + \frac{1}{j100} + \frac{1}{50} - \frac{1}{200} + \frac{1}{j33.33}$$

$$\frac{1}{r} = \frac{2}{50} - \frac{2}{j200} + \frac{4}{j100}$$

$$\frac{1}{r} = \frac{2}{50} - \frac{2}{j200} + \frac{8}{j200}$$

$$\frac{1}{r} = \frac{2}{50} + \frac{6}{j200}$$

$$\frac{1}{r} = \frac{1}{25} + \frac{1}{j33.33}$$

Figure B-8 shows the equivalent circuit after the individual resistances and reactances have been summed. It also shows the vector diagram of the circuit. Again, because the vectors represent parallel impedances, they are shown as reciprocal values. Once you know total circuit resistance and total circuit reactance, you can use Pythagorean's Theorem to calculate total circuit impedance. But keep in mind that you must use the reciprocals of the values in the calculation because you are dealing with parallel circuit impedances.

$$\frac{1}{Z_T} = \sqrt{\left(\frac{1}{R_T}\right)^2 + \left(\frac{1}{X_T}\right)^2}$$

$$\frac{1}{Z_T} = \sqrt{\left(\frac{1}{25}\right)^2 + \left(\frac{1}{33.33}\right)^2}$$

$$\frac{1}{Z_T} = \sqrt{\frac{1}{625} + \frac{1}{1110.9}}$$

$$\frac{1}{Z_T} = \sqrt{\frac{1110.9}{694312.5} + \frac{625}{694312.5}}$$

$$\frac{1}{Z_T} = \sqrt{\frac{1735.9}{694312.5}}$$

$$\frac{1}{Z_T} = \sqrt{0.0025}$$

$$\frac{1}{Z_T} = 0.05$$

$$Z_T = 20\ \Omega$$

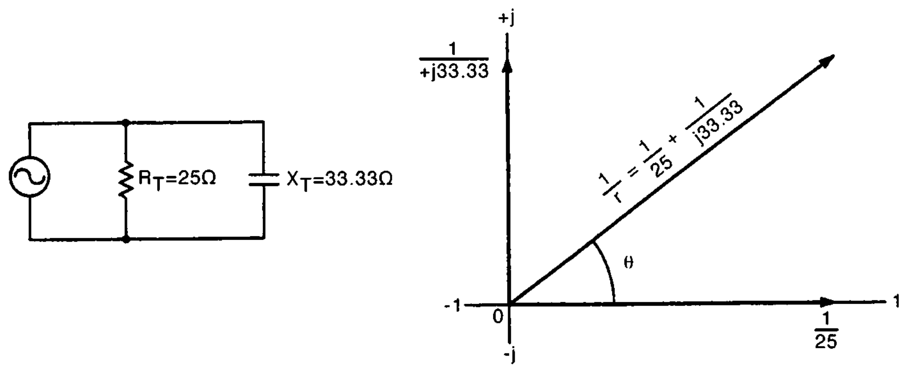


Figure B-8

This short introduction to the j operator showed you that not only can you analyze complex AC circuits graphically, you can do so mathematically. You use the vector plots to help you understand the phase relationship between resistive components, inductive components, and capacitive components. The j operator allows you to reduce several circuit values to one simple complex number. You can then use that number to represent total impedance or voltage in an AC series circuit, and total impedance or current in an AC parallel circuit.

UNIT 6

TRANSFORMERS

CONTENTS

INTRODUCTION

A transformer is a device which transfers AC electrical energy from one circuit to another. It does this through electromagnetic mutual inductance. Generally, the transformer consists of two coils that are positioned close together so that the magnetic field of one coil cuts the other coil. In this way, energy transfers from one coil to the other.

The transformer is the most important single component in electrical distribution systems. It is also widely used in electronics.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define transformer primary, transformer secondary, eddy current loss, and hysteresis.

2. Calculate turns ratio, voltage ratio, power ratio, current ratio, and impedance ratio.

3. Name four types of losses that affect transformer efficiency.

4. Calculate transformer efficiency.

5. Name five uses for transformers.

6. Determine the relationship between voltage, current, and impedance ratios.

7. Name the parts of an elementary transformer.

8. State the difference between a transformer and an autotransformer.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "Transformer Action."	________
☐ Complete Programmed Review Frames 1-9.	________
☐ Read "Transformer Theory."	________
☐ Complete Programmed Review Frames 10-19.	________
☐ Read "Transformer Ratios."	________
☐ Complete Programmed Review Frames 20-35.	________
☐ Read "Transformer Losses."	________
☐ Complete Programmed Review frames 36-42.	________
☐ Read "Transformer Applications."	________
☐ Complete Programmed Review Frames 43-49.	________
☐ Perform Experiment 10: Transformer Characteristics.	________
☐ Study the Summary.	________
☐ Complete the Unit Examination.	________
☐ Check the Examination Answers.	________

TRANSFORMER ACTION

Transformers are used to transfer alternating current from one circuit to another. Normally, some characteristic of the AC signal changes during the transformation process. For example, a low-voltage AC may be stepped-up to a higher value, or a higher voltage may be stepped-down to a lower value. Often it is the current which must change. Transformers are also used to step-up or step-down current. However, a transformer can not step-up or step-down both current and voltage at the same time. In this section, you will take a look at the action which allows the transformer to change voltage and current levels.

Mutual Inductance

The principle upon which transformer action is based is called electromagnetic mutual inductance. You learned about this phenomenon earlier when you studied inductors. First, you will briefly review the principles of mutual inductance.

Recall that when current flows through a conductor, a magnetic field builds up around the conductor. With alternating current, the magnetic field builds, collapses, builds again in the opposite direction, and collapses again for each cycle of the applied current. If you place another conductor in this moving magnetic field, it will have an EMF induced into it.

A transformer is a device that takes advantage of this principle. The two conductors are wound into coils and positioned close together so that the magnetic flux lines of one coil cut the other. Often, the coils are wound one on top of the other. When this is the case, each inductor is coated with a thin insulator material to prevent shorts.

Figure 6-1 illustrates transformer action. Coil L_1 is connected to an AC voltage source. As alternating current flows through the coil, it sets up a varying magnetic field. During one half cycle, current flows through L_1 in the direction shown. This establishes a north magnetic pole at the top of L_1. As the current increases, the field expands outward and cuts the turns of wire in L_2. This induces an EMF into L_2 and in turn, causes current to flow up through the load resistor. Thus, the current in L_1 causes current to flow through L_2.

Note that the coils are wound in opposite directions. The current flows into the top of L_1. This induces a voltage that is negative at the top and positive at the bottom of L_1. This field induces a current into the secondary (L_2) that develops a voltage that is positive at the top and negative at the bottom. The polarity of the secondary voltage causes electrons to flow up through the load resistor. In this type of transformer, the secondary voltage is polarity inverted (180° out of phase) from input to output.

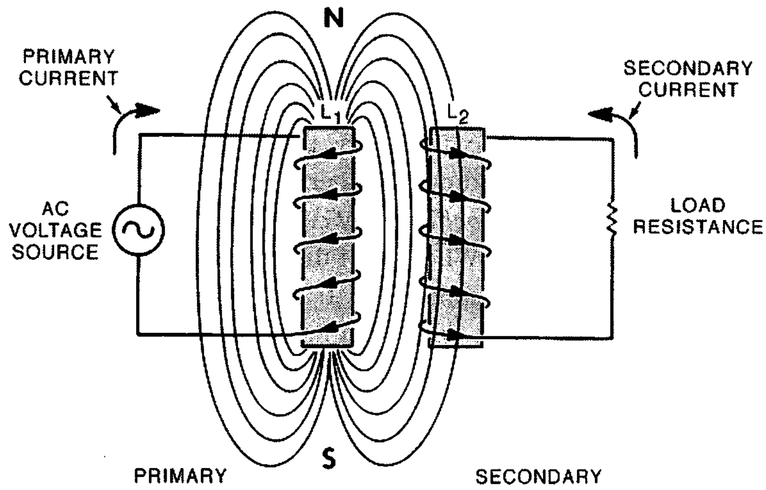


Figure 6-1
Transformer Action.

If you have trouble following the description of transformer operation, review the left hand rules for conductors.

At the end of the first half cycle, the current through L_1 drops to 0 for an instant as the sine wave input passes through 180°. As the current decreases, the field collapses back into L_1. When the current in L_1 decreases, the current through L_2 also decreases.

On the next half cycle, the direction of current through L_1 reverses. This causes a magnetic field of the opposite polarity to expand outward from L_1. Once again, the field cuts the turns of L_2 to induce an EMF. However, because the polarity of the magnetic field is reversed, the polarity of the voltage that is induced into L_2 is also reversed. Thus, the induced EMF causes current to flow down through the load resistance.

Note that the current in L_2 follows the current in L_1. Each time the current in L_1 reverses direction, the current in L_2 also reverses. Therefore, the alternating current in L_2 has the same frequency as the alternating current in L_1. Energy transfers from one circuit to another even though the two circuits are electrically insulated (physically separated) from each other.

The circuit shown in Figure 6-1 is a simple transformer. The coil to which the AC voltage is applied is called the *primary winding*. The AC voltage source causes the current in this winding which is called the *primary current*. The coil into which current is induced is called the *secondary winding*. The induced current is called the *secondary current*.

The amount of EMF that is induced into the secondary winding depends upon the amount of mutual induction between the two coils. In turn, the amount of mutual induction is determined by the degree of *flux linkage* between the two coils. You can think of the flux linkage as the percentage of primary flux lines which cut the secondary winding. Another expression which means approximately the same thing is the *coefficient of coupling*. The coefficient of coupling is a number between 0 and 1. When all of the primary flux lines cut the secondary coil, the coefficient of coupling is 1. If the two coils are positioned so that some of the primary flux lines do not cut the secondary, the coefficient of coupling is less than one.

The coefficient of coupling and the resistive properties of the coils account for the statement that "input (primary) power is always more than the output (secondary) power."

Figure 6-2 illustrates that the amount of mutual inductance depends upon the flux linkage or the coefficient of coupling. In Figure 6-2A, the secondary coil, L_2, is wound directly on the primary coil, L_1. With this arrangement, nearly all of the flux lines that are produced by the primary cut the secondary windings. Therefore, the coefficient of coupling is close to one.

In Figure 6-2B the transformer consists of two coils. Here, only a few lines of flux from the primary cut the secondary. Therefore, the coefficient of coupling is low.

Figure 6-2C illustrates that when you place the two windings far enough apart, there is no flux linkage between them. In this case, there is no mutual inductance and the coefficient of coupling is zero. While this arrangement has no practical purpose, it illustrates the importance of the coefficient of coupling. Remember also that when coils are mounted perpendicular to each other the coefficient of coupling is zero.

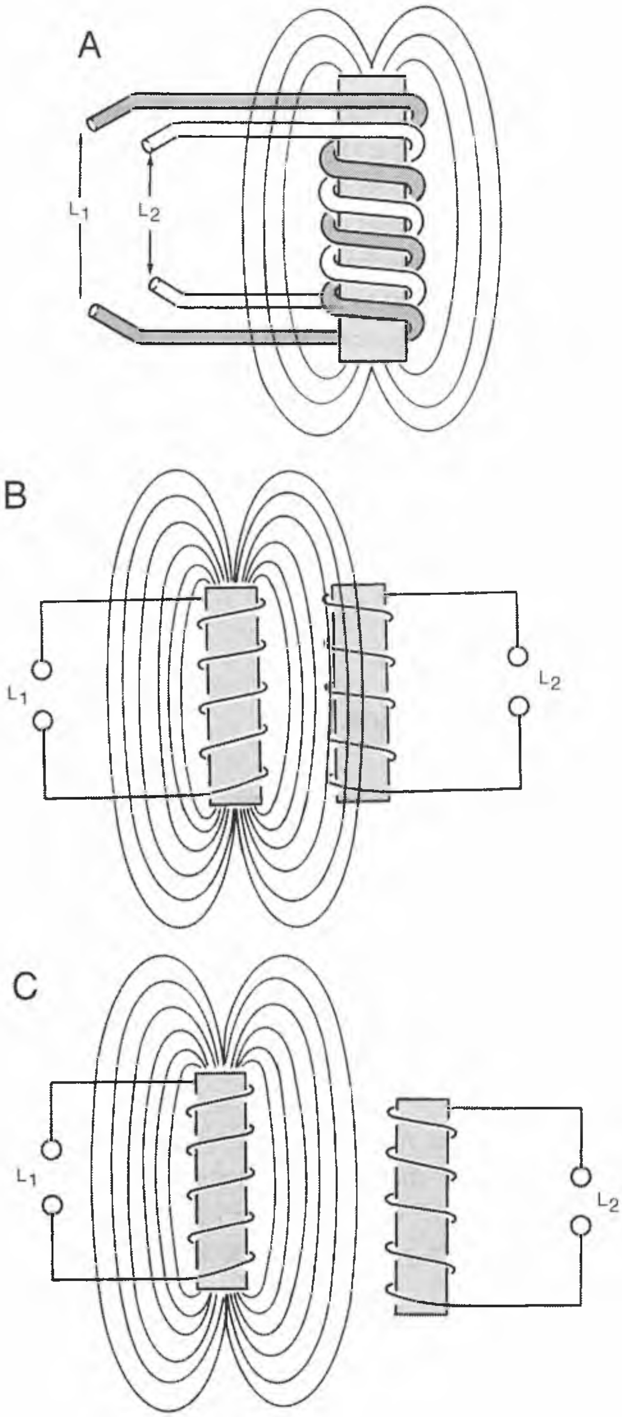


Figure 6-2
Mutual induction depends
upon the coefficient of coupling.

Transformer Action

Figure 6-3 illustrates the step-by-step sequence of events in transformer action. When you close the switch, the EMF of the generator is applied across the primary. This causes current to flow through the primary. The current produces magnetic flux lines which expands outward and cut the secondary. This induces an EMF into the secondary winding. When a path for current flow exists, the EMF causes a secondary current to flow. A load is connected across the secondary. Energy transfers from the generator to the load even though the two circuits are not physically connected.

Transformers are not used in DC circuits because, except for initial turn on and turn off of the source voltage, there is no movement of flux lines. When there is no relative motion (expanding and collapsing) of the magnetic field, there is no induced voltage. Therefore, the transformer is considered to be an AC component.

Transformer Construction

Construction techniques for transformers vary depending upon the type of transformer and the particular application. You cannot use all transformers for the same application. A substation transformer in a power distribution system may approach the size of a small house. On the other hand, an IF transformer in a transistor radio may be no larger than a pencil eraser. In spite of the vast size difference, these two transformers operate on the same basic principle. Both have primary and secondary coils. In both, energy is coupled from the primary to the secondary by mutual inductance.

The frequency a transformer must pass, the voltage and current involved, and several other factors dictate the design of a transformer. A power transformer may be required to handle 115 VAC 60 Hz, at 1 ampere. On the other hand, an IF transformer may work with a frequency of 455 kHz at a few millivolts and a few microamperes.

Transformers are bulky, heavy, and expensive when they are compared to other electronic components. Therefore, they are used only in limited applications.

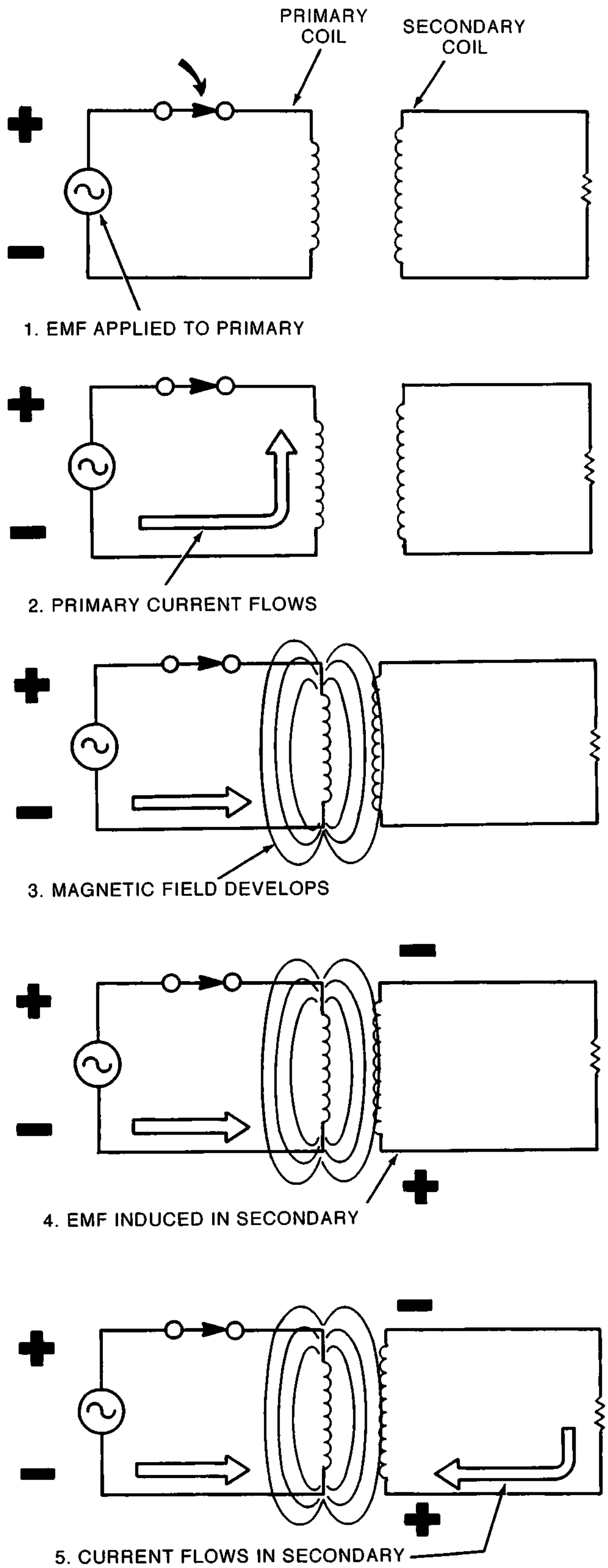


Figure 6-3
Sequence of events
in transformer action.

Figure 6-4 compares the construction of an iron-core transformer to an air core transformer. The iron-core transformer is much larger and heavier. The primary winding is wound on one arm of the core. The secondary is wound directly on top of the primary. Note that the symbol for the transformer shows the two coils. The two lines between the coils represent the iron core. The iron core concentrates the lines of force into a small area. Recall from you study of inductance that iron has a high permeability which means it is easy to magnetize.

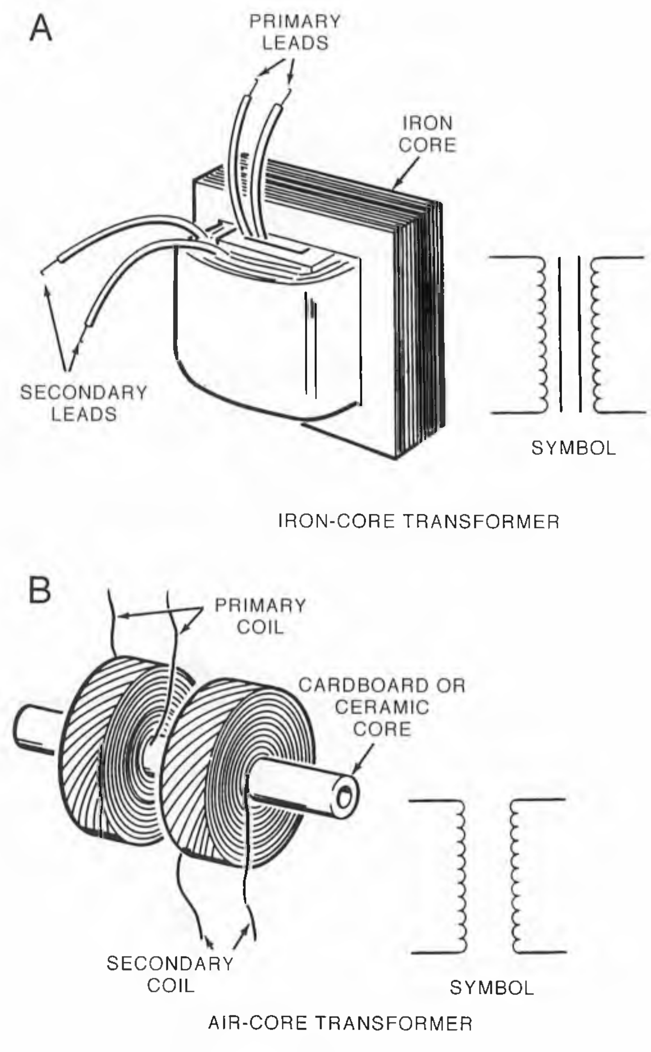


Figure 6-4
Two typical transformer
and their symbols.

The construction of the air-core transformer is different. It is designed to be used at much higher frequencies. Iron core losses increase as frequency increases. Transformers which are designed to operate at high frequencies use little or no iron in the core. Instead, a non-conductive material that has the same permeability as air is used. High-frequency cores are usually either ceramic or simply small cardboard tubes.

Programmed Review

1. A device which couples AC energy from one circuit to another through electromagnetic mutual induction is called a __________.

2. (transformer) A transformer consists of two coils which are wound on a core material. The winding to which you apply an input alternating current is called the __________ winding.

3. (primary) The winding into which an EMF is induced and from which you take an output is called the __________ winding.

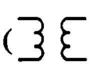
4. (secondary) Generally, the current and voltage in the secondary are different from that in the primary. However, the __________ is always the same in both the primary and secondary.

5. (frequency) Transformers which are designed to work at low frequencies generally have __________ cores.

6. (iron) Those that are designed for high-frequency operation generally have __________ cores.

7. (air) Draw the schematic symbol for an iron-core transformer in the space below.

8. () Draw the schematic symbol for an air-core transformer in the space below.

9. ()

TRANSFORMER THEORY

In the previous section you saw how you can use transformer action to couple an AC signal from one circuit to another. In this section, you will explore this action further.

Transformer With No Load

Figure 6-5A shows a transformer being operated without a load, which means the secondary of the transformer is open. Therefore, there is no secondary current. Even so, there is primary current because the primary is connected across an AC voltage source.

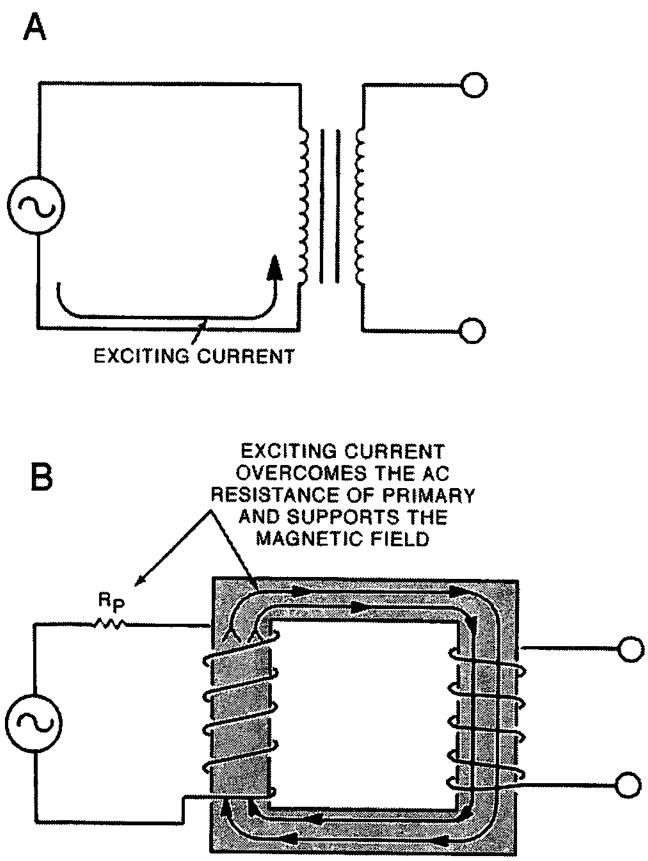


Figure 6-5
Transformer with no load.

In this case, the impedance of the transformer's primary and the applied voltage determine the amount of primary current. Since no power is being used in the secondary, the primary acts like an inductor. The primary of a typical iron-core transformer can have an inductance of several henrys. This tends to keep the primary current very low.

In addition to the inductance, the primary winding has a certain value of AC resistance which limits the current even further. The small amount of primary current that flows with no load is called the excitation current. Figure 6-5B illustrates two functions that the exciting current must perform. First, it overcomes the AC resistance of the primary. In Figure 6-5B, the resistance of the inductor is shown as a separate resistor. This resistance dissipates power in the form of heat. Secondarily, the exciting current supports the magnetic field in the core.

The X_L of the primary is normally much larger than its AC resistance. Thus, the exciting current lags behind the applied voltage by almost 90°. Consequently, when no current flows in the secondary, the primary of the transformer acts like an inductor.

When you studied inductors, you learned that the current lags the applied voltage due to the counter EMF that is produced by the coil. The following paragraphs briefly review this principle.

In Figure 6-5B, the applied EMF causes current to flow in the primary winding. In turn, this current establishes the magnetic field. However, as the magnetic field expands outward, it cuts the primary winding and induces a counter EMF. This counter EMF opposes the applied EMF. Thus, the primary current lags behind the applied voltage.

This is the situation which occurs when there is no secondary current. However, when secondary current flows, these conditions change and the transformer operates differently. Since the transformer is normally operated with a secondary load, you must understand why it operates differently when secondary current flows.

Transformer With Load

Figure 6-6 shows a simple transformer with a load resistor connected across the secondary winding. When AC current flows in the primary, it induces a current into the secondary. You will now see how the current in the secondary affects the operation of the transformer.

In Figure 6-6A, the polarity of the applied voltage is negative at the top of the primary and positive at the bottom. This forces current to flow down through the primary winding. When you use the left-hand rule that was developed earlier, you find that the current develops a magnetic field in the direction shown.

As this magnetic field expands outward, it induces a counter EMF into the primary winding. This counter EMF opposes the applied EMF. Although the applied EMF forces current to flow down through the primary, the counter EMF tries to force current up through the primary. The net result is a small current which flows down through the primary.

Note that the secondary is wound directly on top of the primary. Therefore, the expanding magnetic field that is caused by the primary current also cuts the secondary winding. Since the secondary is wound in the same direction as the primary, the EMF induced into secondary has the same polarity as the counter EMF in the primary. Thus, the induced current in the secondary flows in the direction shown.

Note that in this configuration there is no polarity inversion between the primary and secondary windings.

The current flow in the secondary establishes a magnetic field of its own as shown in Figure 6-6B. With the left-hand rule, you can verify that the magnetic field has the polarity shown. As the magnetic field expands, it cuts the secondary winding and induces a counter EMF. This counter EMF tries to force current to flow down through the secondary in opposition to the induced current.

The expanding flux in the secondary also cuts the primary turns. This induces yet another EMF back into the primary winding. This induced EMF is in the same direction as the counter EMF of the secondary. Thus, this EMF tends to force current to flow down through the primary. If you kept track of the various EMFs, you will see that the EMF that is induced into the primary from the secondary opposes the counter EMF that was originally developed in the primary. Or stated another way, the current that is induced into the primary, from the secondary, aids the original primary current. This causes the primary current to increase.

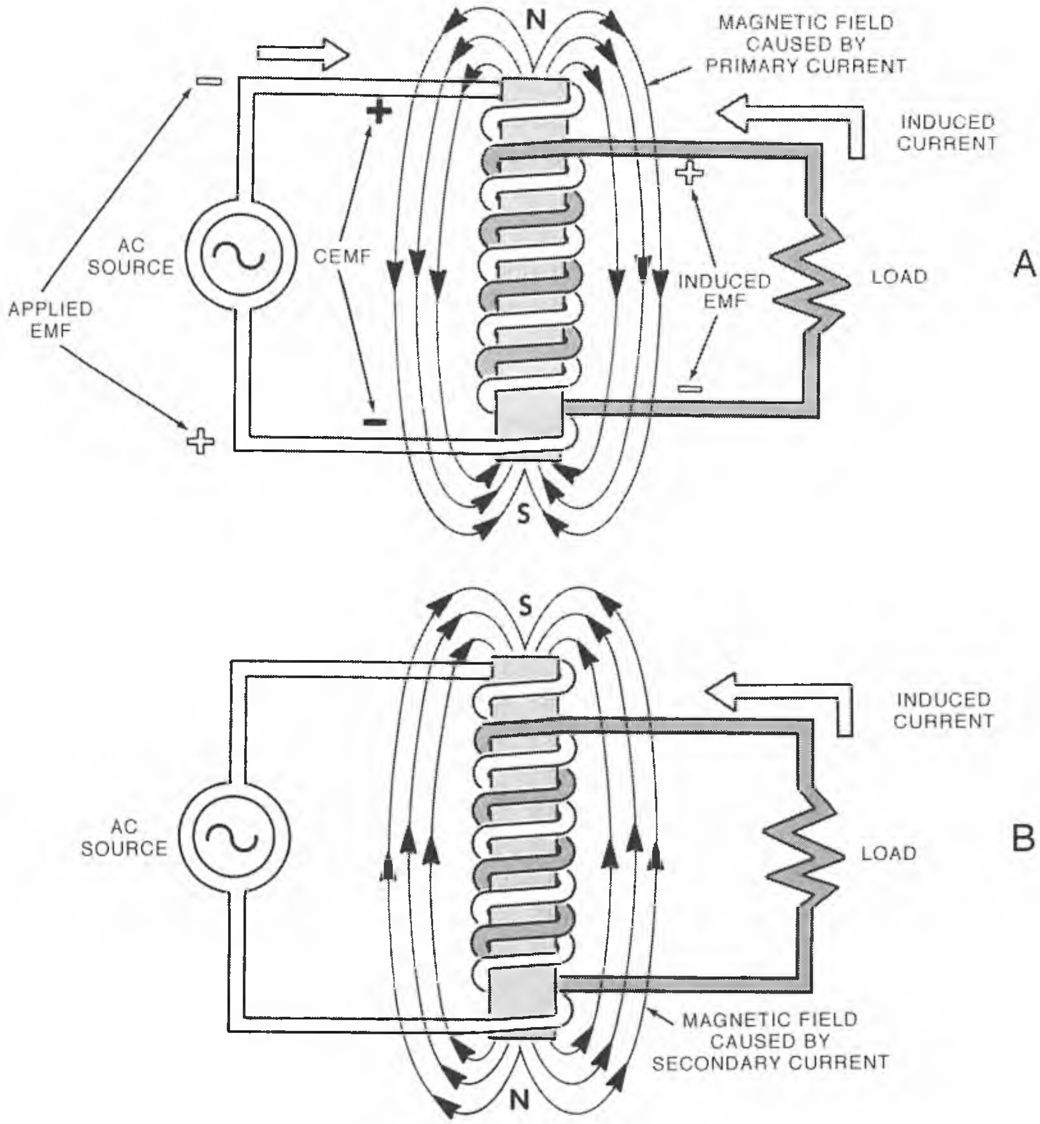


Figure 6-6
Mutual inductance.

This increase in primary current is caused by the expanding magnetic field of the secondary. The more current that flows in the secondary, the stronger the secondary magnetic field. This, in turn, increases the primary current. Consequently, an increase in secondary current causes an increase in primary current. Later, you will see that the exact amount of increase in each depends upon the turns ratio.

The sum of the effects that were just described is called mutual inductance. The inductance is mutual because the primary induces a voltage into the secondary and, simultaneously, the secondary induces a voltage back into the primary.

To be certain you have the idea, review this process once more.

Step 1. AC in the primary establishes a fluctuating magnetic field.

Step 2. The varying flux induces a counter EMF into the primary and an EMF into the secondary.

Step 3. The induced EMF causes current to flow in the secondary.

Step 4. The current in the secondary establishes a magnetic field which is opposite to the field caused by the primary current.

Step 5. The secondary flux induces an EMF back into the primary which opposes the counter EMF of step 2. This decreases the primary counter EMF.

Step 6. Primary current increases because the counter EMF decreases.

Programmed Review

10.	When you operate a transformer without a load on the secondary, the primary winding acts like an ___________ .
11.	(inductor) A small current which flows through the primary winding is called the ___________ current.
12.	(exciting) Its function is to support the magnetic field and overcome the AC ___________ of the primary.
13.	(resistance) When a load is connected to the secondary, the primary current ___________ . (increases/decreases)
14.	(increases) When secondary current flows, a secondary magnetic field develops which is in the ___________ (same/opposite) direction as the primary magnetic field.
15.	(opposite) The secondary magnetic field induces an EMF into the primary which opposes the ___________ EMF of the primary.
16.	(counter) Since this reduces the counter EMF, the primary current will ___________ . (increase/decrease)
17.	(increase) The interaction of the two magnetic fields is called ___________ induction.
18.	(mutual) When the current in the secondary increases, the current in the primary ___________ . (increases/decreases)
19.	(increases)

TRANSFORMER RATIOS

Transformers have many applications. You can use them to step-up or step-down voltage, step-up or step-down current, or make one value of impedance appear to be another value. In each case, you are concerned with a ratio. In the first case, the ratio is that of an input voltage to an output voltage. In the second case, the ratio is that of a primary current to a secondary current. In the third case, the ratio is that of an input impedance to an output impedance. The number of turns in the primary winding compared to the number of turns in the secondary determine each of these ratios.

Voltage Ratio

Transformers are frequently used to step-up or step-down voltages. Most electronic devices are powered by 115 VAC at 60 Hz. Some applications require higher voltages, while others can get by with much lower voltages. You can use a transformer to transform the 115 VAC to whatever value you require.

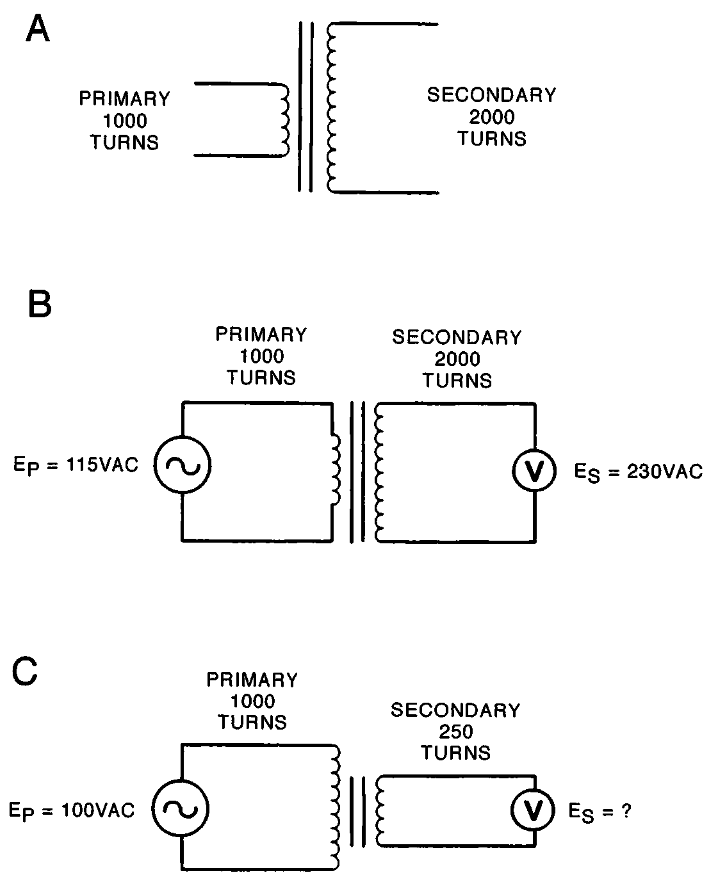


Figure 6-7
The voltage ratio is determined by the turns ratio.

When the output (secondary) voltage is higher than the input (primary) voltage, the transformer is a *step-up* transformer. The amount of step-up is determined by the *turns ratio* of the transformer.

Figure 6-7A illustrates the turns ratio of a typical transformer. Note that the primary consists of 1,000 turns of wire while the secondary has 2,000 turns. The turns ratio is defined as the ratio of the number of turns in the secondary, N_S, to the number of turns in the primary, N_P; that is:

$$\text{Turns ratio} = \frac{N_S}{N_P}$$

Therefore, in Figure 6-7A, the turns ratio is:

$$\text{Turns ratio} = \frac{N_S}{N_P} = \frac{2000}{1000} = 2$$

This is expressed as a turns ratio of "2 to 1" or 2:1. When the secondary has more turns than the primary, the voltage is "stepped-up." For example, When the turns ratio is 2:1, the secondary voltage will be twice as high as the primary voltage. Therefore, the voltage ratio is equal to the turns ratio. The voltage ratio is directly proportional to the turns ratio and is expressed by the equation:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

In some cases, it is more convenient to think of the turns ratio as $\frac{N_P}{N_S}$.

When you do this, the voltage ratio equation is:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

You can use either of these equations to find the secondary voltage when you know the turns ratio and the primary voltage. Figure 6-7B shows 115 VAC applied to the primary. To find the secondary voltage, rearrange the formula like this:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

$$E_S = \frac{N_S}{N_P} \times E_P$$

$$E_S = \frac{2000}{1000} \times 115\text{V}$$

$$E_S = 2 \times 115\text{V}$$

$$E_S = 230\text{V}$$

With the proper turns ratio, you can step-up the input voltage to any value you require.

Remember that AC voltages are understood to be rms or effective values unless otherwise specified. You should also recognize the 115 voltage value as the effective voltage that is available in most homes and industry. On many pieces of equipment, you may have noticed a power function switch that is labeled 115/230. This switch selects the desired turns ratio (either 1:1 or 2:1).

You can also use a transformer to step down a voltage. To accomplish this, the secondary should have fewer turns than the primary. For example, in Figure 6-7C, the primary has 1,000 turns while the secondary has 250 turns. The primary voltage is given as 100 VAC. Here's how you find the secondary voltage:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

$$E_S = \frac{N_S}{N_P} \times E_P$$

$$E_S = \frac{250}{1000} \times 100V$$

$$E_S = \frac{1}{4} \times 100V$$

$$E_S = 25V$$

The above equations hold true as long as the coefficient of coupling is high and the transformer losses are low. To be completely accurate, the transformer must have a coupling coefficient of 1 and an efficiency of 100%. While these conditions are impossible to achieve in practice, some transformers come very close. This section assume an ideal transformer. Later, you will see that general purpose transformers fall far short of the ideal transformer. General purpose transformers have efficiency ratings between 60 and 80%.

Power Ratio

When you ignore the losses in the transformer, the power in the secondary is the same as the power in the primary. Therefore, in the ideal transformer the power ratio is 1. Although the transformer can step-up voltage, it cannot step-up power. You can never take more power from the secondary than you put in at the primary. Therefore, when a transformer steps-up a voltage, it steps-down the cur-

rent. Therefore, you can assume the output power to be the same as the input power. This is expressed by the equation:

$$P_P = P_S$$

where P_P is the power in the primary and P_S is the power in the secondary.

Current Ratio

A transformer which steps-up voltage must at the same time step-down current. Otherwise, it would deliver more power in the secondary than is supplied by the primary.

You can derive an equation for the current ratio to prove. Remember that when you ignore losses:

$$P_P = P_S$$

Recall that the formula for power is $P = EI$. Thus the power in the primary equals $E_P \times IP$ while the power in the secondary equals $E_S \times I_S$. Therefore, if $P_P = P_S$:

$$E_P \times I_P = E_S \times I_S$$

The voltage ratio equation is:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

Transposing:

$$E_S = \frac{N_S}{N_P} \times E_P$$

Now substitute this expression for E_S in the previous equation:

$$E_P \times I_P = \frac{N_S}{N_P} \times E_P \times I_S$$

Dividing both sides by E_P, provides:

$$\frac{\cancel{E_P} \times I_P}{\cancel{E_P}} = \frac{\frac{N_S}{N_P} \times \cancel{E_P} \times I_S}{\cancel{E_P}} \quad \text{or} \quad I_P = \frac{N_S}{N_P} \times I_S$$

Dividing by I_S, provides:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

This states that the current ratio is inversely proportional to the turns ratio. Voltage is directly proportional to turns ratio. This makes sense because more turns means more wire and more wire means more resistance. Anytime resistance increases current decreases.

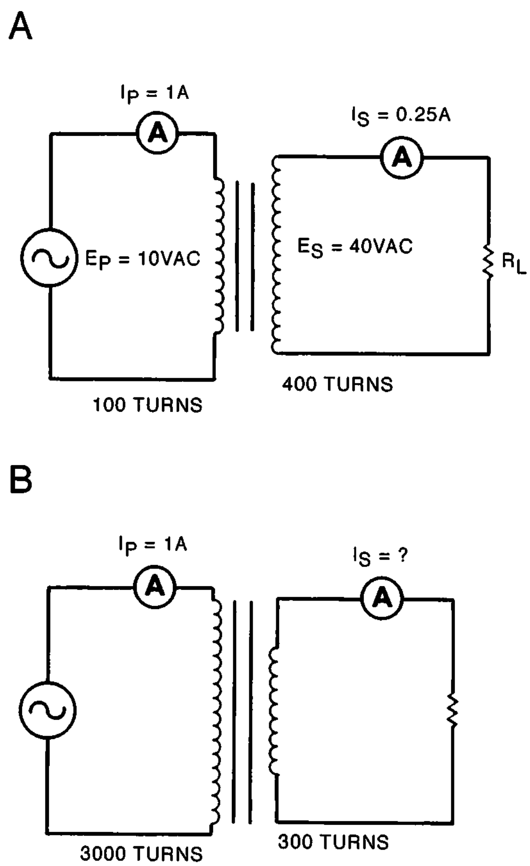


Figure 6-8
The turns ratio determines the current ratio.

Figure 6-8A shows a transformer with a turns ratio of 4:1. This means that the secondary has 4 times as many turns as the primary. Therefore, the voltage is stepped-up by a factor of four, from 10 V to 40 V. However, the current is stepped-down from 1 ampere in the primary to only 0.25 amperes in the secondary. You can rearrange the current ratio formula to prove this:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

Cross multiplying provides:

$$I_S\,(N_S) = I_P\,(N_P)$$

Dividing by N_S provides:

$$I_S = \frac{I_P\,(N_P)}{N_S}$$

$$I_S = \frac{N_P}{N_S} \times I_P$$

$$I_S = \frac{100}{400} \times 1A$$

$$I_S = \frac{1}{4} \times 1A$$

$$I_S = 0.25A$$

You can also use a transformer to step-up current. However to do this, it must step-down voltage. To step-up current, the primary must have more turns than the secondary as shown in Figure 6-8B. The secondary current is:

$$I_S = \frac{N_P}{N_S} \times I_P$$

$$I_S = \frac{3000}{300} \times 1A$$

$$I_S = 10 \times 1A$$

$$I_S = 10A$$

Solving Transformer Problems

Once you understand how to use the voltage and current ratio formulas, you can solve a wide variety of transformer problems. For example, consider the circuit shown in Figure 6-9A. The number of turns, I_S, and the value of R are given. You wish to find E_P and I_P.

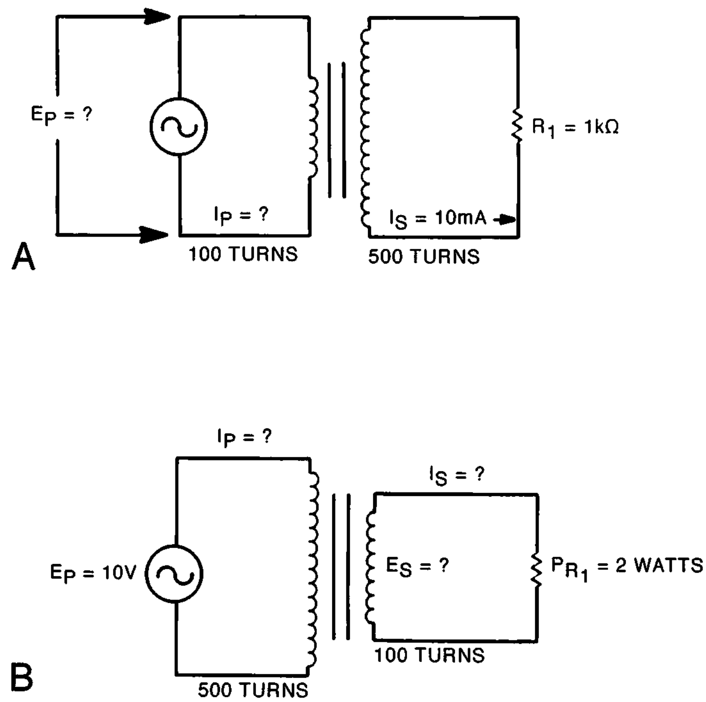


Figure 6-9
Solving transformer problems.

You can determine I_P immediately since I_S and the turns ratio are given:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

$$I_P = \frac{N_S}{N_P} \times I_S$$

$$I_P = \frac{500}{100} \times 10\text{ mA}$$

$$I_P = 5 \times 10\text{ mA}$$

$$I_P = 50\text{ mA}$$

Since you know the turns ratio, you can find E_P if you know E_S.

$$E_S = I_S (R_1)$$

$$E_S = 10 \text{ mA} \times 1 \text{ k}\Omega$$

$$E_S = 10 \text{ V}$$

Now you can find E_P:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

Cross multiplying:

$$E_S (N_P) = E_P (N_S).$$

Dividing by N_S provides:

$$\frac{E_S (N_P)}{N_S} = E_P$$

Rearranging the equation provides:

$$E_P = \frac{N_P}{N_S} \times E_S$$

$$E_P = \frac{100}{500} \times 10\text{V}$$

$$E_P = \frac{1}{5} \times 10\text{V}$$

$$E_P = 2\text{V}$$

Figure 6-9B shows another problem. Here, the turns ratio, the primary voltage, and the power dissipated in the secondary circuit are given. You want to find the secondary voltage, the secondary current, and primary current, and the value of R_1.

Because the turns ratio and E_P are given, you can compute the value of E_S:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

$$E_S = \frac{N_S}{N_P} \times E_P$$

$$E_S = \frac{100}{500} \times 10\text{V}$$

$$E_S = \frac{1}{5} \times 10\text{V}$$

$$E_S = 2\text{V}$$

Once you know E_S, you can compute I_S:

$$P_S = E_S \times I_S$$

$$I_S = \frac{P_S}{E_S}$$

$$I_S = \frac{2W}{2V}$$

$$I_S = 1A$$

When you know I_S and the turns ratio, you can compute I_P:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

$$I_P = \frac{N_S}{N_P} \times I_S$$

$$I_P = \frac{100}{500} \times 1A$$

$$I_P = \frac{1}{5} \times 1A$$

$$I_P = 0.2A$$

You can now use Ohm's Law to compute the value of R_1:

$$R_1 = \frac{E_S}{I_S}$$

$$R_1 = \frac{2V}{1A}$$

$$R_1 = 2\Omega$$

or, you can rearrange the power formula to find the same value:

$$P = I^2 R$$

$$R = \frac{P}{I^2}$$

$$R = \frac{2W}{1A^2}$$

$$R = 2\Omega$$

Impedance Ratio

In electronics, one of the most important applications of a transformer is impedance matching. Maximum power is transferred from a generator to a load, when the impedance of the generator matches the impedance of the load. When impedances do not match, power is wasted.

There are many cases in electronics in which the impedance of the signal source or generator, does not match the load which it must drive. For example, a transistor amplifier stage might be most efficient when it drives a 100-ohm load. Nevertheless, the amplifier may be required to drive a 4-ohm speaker. This is a mismatch that results in wasted power and inefficient operation.

You can use a transformer to correct for this mismatched impedance. The transformer can make one value of impedance appear to be another value. In the above example, a transformer is placed between the transistor amplifier and the speaker. When you choose the proper turns ratio, the transformer can make the 4-ohm speaker appear to be a 100-ohm load to the transistor amplifier.

You have seen that the voltage or current step-up of a transformer depends upon the turns ratio. The impedance matching capability of a transformer also depends upon the turns ratio. However, the impedance ratio is equal to the turns ratio squared. That is:

$$\frac{Z_P}{Z_S} = \left(\frac{N_P}{N_S}\right)^2$$

Where Z_P is the impedance of the primary circuit, Z_S is the impedance of the secondary circuit, and $\frac{N_P}{N_S}$ is the primary to secondary turns ratio.

You can rearrange the formula to provide:

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}$$

You can use this equation to solve impedance-matching problems, such as the one described earlier. The problem is to find a turns ratio that matches a 100-ohm generator (such as the transistor amplifier) to a 4-ohm load (such as a speaker). You can solve this type of problem with the formula:

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}$$

$$\frac{N_P}{N_S} = \sqrt{\frac{100\,\Omega}{4\,\Omega}}$$

$$\frac{N_P}{N_S} = \sqrt{25}$$

$$\frac{N_P}{N_S} = 5$$

This is a primary to secondary turns ratio of 5:1. Therefore, when the number of primary turns is 5,000, the number of secondary turns must be 1,000. As you can see, any transformer with a turns ratio of 5:1 has an impedance ratio of $(5)^2$:1 or 25:1.

Now consider another example. Suppose you need to match a generator that has an impedance of 6,000 ohms to a 60-ohm load. The needed turns ratio is:

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}$$

$$\frac{N_P}{N_S} = \sqrt{\frac{6000}{60}}$$

$$\frac{N_P}{N_S} = \sqrt{100}$$

$$\frac{N_P}{N_S} = 10$$

The turns ratio must be 10:1. The primary must have 10 times as many turns as the secondary.

Impedance matching is one of the most important applications of a transformer. With the proper turns ratio, transformers can match a wide range of impedances.

Programmed Review

20. You can use transformers to step-up or step-down voltage. When you use them as a step-up transformer, the secondary has ___________ turns that the primary. more/fewer

21. (more) If you ignore losses, the voltage ratio between the primary and secondary is directly proportional to the ___________ ratio.

22. (turns) Stated as a formula, $\frac{E_S}{E_P} =$ ___________.

23. $\left(\frac{E_S}{E_P} = \frac{N_S}{N_P}\right)$ If 10 volts is applied to the primary of a transformer which has 100 primary turns and 1000 secondary turns, the secondary voltage will be ___________ volts.

24. (100) If you ignore losses, the power in the secondary of a transformer is the same as the power in the ___________.

25. (primary) For this reason, a transformer which steps-up voltage must step-down ___________.

26. (current) Therefore, the current ratio is ___________ proportional to the turns ratio. inversely/directly

27. (inversely) Stated as a formula, $\frac{I_P}{I_S} =$ ___________.

28. $\left(\frac{I_P}{I_S} = \frac{N_S}{N_P}\right)$ If the primary current is 1 ampere and the primary has 10 times as many turns as the secondary, the secondary current will be ___________ amperes.

29. (10) To transfer maximum power from a source to a load, the impedance of the source must match the impedance of the __________.

30. (load) For this reason, an important application of transformers is __________ matching.

31. (impedance) The impedance ratio of a transformer equals the __________ __________ squared.

32. (turns ratio) Or, stated another way, the turns ratio equals the square root of the __________ ratio.

33. (impedance) Stated as an equation, $\frac{N_P}{N_S} =$ __________.

34. $\left(\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}\right)$ Therefore, to match an 800-ohm source to a 16-ohm load requires a turns ratio of about __________:__________.

35. (7:1)

TRANSFORMER LOSSES

Transformers which are used in electronic circuits are very efficient devices. An efficiency of ninety percent or better is normal. All transformers have some losses. In many cases, these losses dictate transformer design. Power transformers in particular are designed to minimize losses. The losses are separated into several categories.

Core Losses

In power transformers, the largest loss occurs in the transformer's core. Even so, a much larger core loss would occur if it were not for special construction techniques. Core losses can be divided into two separate parts. You will examine each of these losses.

EDDY CURRENT LOSSES

The cores of power transformers are generally made of soft iron or steel. Because iron and steel are good conductors, and are ferromagnetic, a current can be induced into the core. This occurs when the core is subjected to a moving magnetic field. As you saw, a moving magnetic field is a requirement in all transformers. Unless manufacturers take special precautions, large circulating currents are induced into the core of the transformer. These induced circulating currents are called eddy currents.

Figure 6-10 shows how eddy currents are induced into the core. When alternating current flows through the winding, a changing magnetic field develops around the core. As this field expands and contracts, it induces a voltage into the core. The induced EMF causes eddy currents to flow as shown. These eddy currents are sometimes referred to as skin effect because they flow along the conductor's surface.

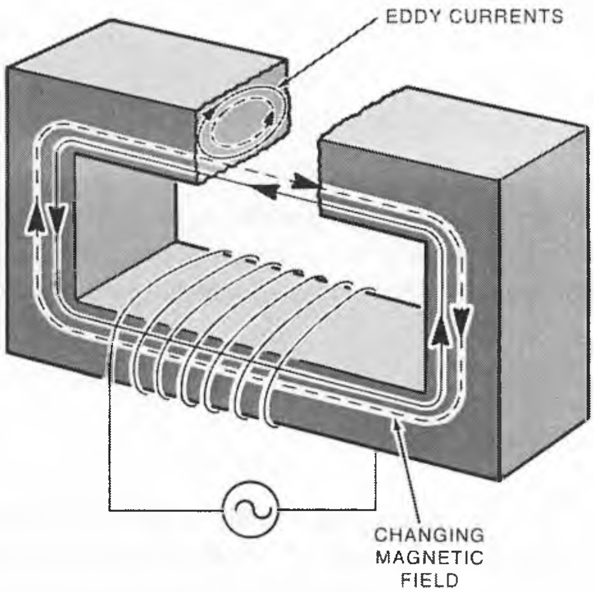


Figure 6-10
Eddy currents are induced in the core by the changing magnetic field.

Manufacturers can change the construction of the core to reduce eddy currents. In Figure 6-10, the core is a solid block of metal. Because the cross sectional area of the core is large, it has very little resistance and large eddy currents flow.

The eddy currents produce a power loss that is proportional to the current squared ($P = I^2R$). When you reduce the eddy currents, the power loss is less.

Eddy currents are reduced when the core consists of many thin sheets of metal rather than a solid block of metal. Figure 6-11 illustrates how this reduces the eddy currents. Figure 6-11A shows large eddy currents flowing through the low-resistance solid core. However, you can use several thin sheets to form a core that has the same magnetic characteristics as shown in Figure 6-11B.

The individual sheets are coated with an insulating varnish so that no current can flow between the sheets. Thus, any eddy currents that are produced are restricted to a single sheet of metal. Because the cross sectional area of a sheet is quite small, the resistance of each sheet is relatively high. This high resistance keeps the magnitude of the eddy currents low. Consequently, the power loss is much lower when the core is made of thin laminated (insulated) sheets.

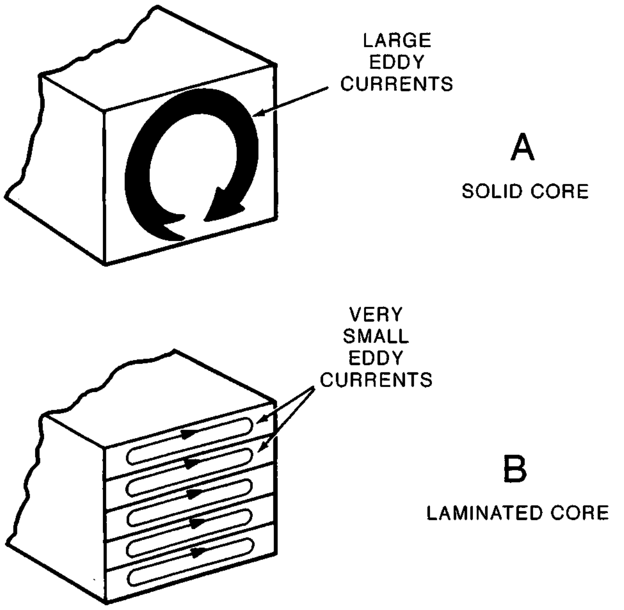


Figure 6-11
You can laminate the core to reduce eddy currents.

The thin sheets that make up the core are called laminations. A laminated iron core is shown in Figure 6-12. The lamination gets its name from its shape. Frequently, an iron core is made up of a combination of "E" and "I" laminations as shown. Remember, the purpose of laminating a core is to reduce the power loss that is caused by eddy currents.

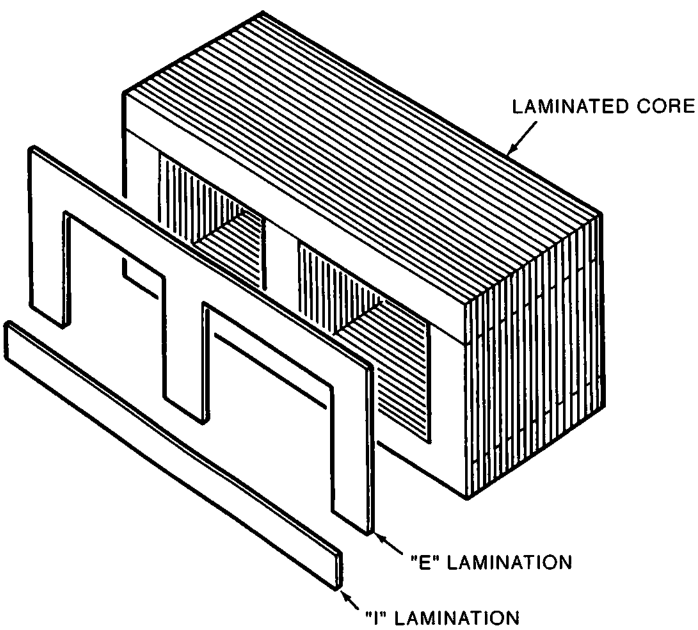


Figure 6-12
Core construction.

HYSTERESIS

Another type of loss that occurs in the core of a transformer is called hysteresis. When iron is not magnetized, its magnetic domains are arranged in a random pattern. However, when a magnetizing force is applied, the domains are lined up by the magnetic field. When the magnetic field reverses, the domains must also reverse their alignment.

In a transformer, the magnetic field reverses direction many times each second. The frequency of the applied AC source determine the number of reversals per second. For example, with a 60-hertz source, the magnetic field reverses 120 times per second. Remember, the magnetic field reverses twice each cycle. When it reverses direction, the domains must overcome friction and inertia. While it does this, a certain amount of power is dissipated in the form of heat. This power loss is referred to as the *hysteresis loss.*

The terms friction and inertia refer to the basic laws of physics that state "a body at rest tends to remain at rest" and "a body in motion tends to remain in motion". Therefore, anytime you have relative motion there is friction and inertia. They are a form of resistance to motion and they do cause power to be dissipated.

Some materials, such as soft iron, normally have high hysteresis losses. The hysteresis loss in steel is lower than soft iron. Some large power transformers use a special type of metal called silicon steel because it has a low hysteresis loss.

The amount of loss that is caused by hysteresis increases as frequency increases. An iron-core transformer that has a small hysteresis loss at low frequencies, may have a large hysteresis loss at higher frequencies. Hysteresis loss is directly proportional to frequency.

Copper Loss

Another type of loss that is present in all transformers is called *copper loss.* The resistance of the copper wire in the primary and secondary windings causes this loss. A transformer winding can consist of hundreds of turns of fine copper wire. Due to the length of the wire and its small cross sectional area, its resistance can be quite high. As current flows through this resistance, some power is dissipated in the form of heat. The formula $P = I^2R$ determines the amount of power that is dissipated in the form of heat. For this reason, another name for copper loss is the *I^2R loss.*

The amount of copper loss is proportional to the current squared. When the current through a transformer doubles, the copper loss increases by a factor of 4.

To reduce copper loss, you can increase the size (reduce the wire gauge number) of the copper wire you use for the windings. The larger the diameter of the wire, the smaller its resistance. As you can see by the formula, dissipated power and resistance are directly proportional. When you decrease resistance, you decrease the I^2R loss. Another method you can use to reduce copper or I^2R loss, is to keep the current in the transformer as low as possible.

External Induction Loss

As the magnetic field expands and contracts around the transformer, it often cuts an external conductor of some kind. When a current is induced into an external conductor, some power is taken from the transformer circuit. In most cases, the power that is lost by external induction is so small that you can ignore it. However, the voltage that is induced into outside circuits can be bothersome. For example, in a sensitive amplifier circuit, the unwanted induced voltage from a transformer may interfere with the signal you are trying to amplify.

Shielding can reduce interference that is caused by magnetic induction. Often, sensitive circuits are placed inside a metal shield which prevents stray magnetic fields from reaching the circuits. Also, transformers themselves are often placed in thin metal housings to prevent magnetic fields from escaping.

Earlier, you used a high-permeability material (soft iron) to form a core to concentrate the magnetic force lines into a magnetic field close to the inductor. In this case, the flux lines are prevented from cutting the external conductor. These shields are called permeability shields. Remember, magnetic flux lines cannot be blocked, but they can be rerouted.

Transformer Efficiency

Due to transformer losses, more power is applied to the primary of the transformer than is available for use in the secondary. All transformers have power losses. Hence, the *efficiency* of a transformer is always less than 100%.

The efficiency of a transformer is the ratio of output power to input power. For example, when a transformer has an input power of 110 watts and an output power of 105 watts, its efficiency is:

$$\text{efficiency} = \frac{\text{power output}}{\text{power input}} = \frac{105\text{W}}{110\text{W}} = 0.9545$$

Efficiency is normally stated in terms of a percentage (%). Therefore, you must multiply the decimal fraction by 100 to convert it to a percentage. The input power is the primary power. The output power is the secondary power. The formula for a transformer's percent of efficiency is:

$$\%\ \text{efficiency} = \frac{P_S}{P_P} \times 100$$

P_P is the power in the primary, or input power. P_S is the power in the secondary, or output power. Therefore, in the above example,

$$\%\ \text{efficiency} = \frac{P_S}{P_P} \times 100$$

$$= \frac{105\text{W}}{110\text{W}} \times 100$$

$$= .9545 \times 100$$

$$= 95.45\%$$

Programmed Review

36. The two factors which make up core losses are ___________-___________ losses and ___________ losses..
37. (eddy-current, hysteresis) You can use a ___________ core to reduce eddy currents.
38. (laminated) Hysteresis loss is causes by the constant reversal of the magnetic ___________ within the core material.
39. (domains) Copper losses are caused by the AC ___________ of the primary and secondary windings of the transformer.
40. (resistance) Due to these losses, the ___________ of the transformer is less than 100%.
41. (efficiency) A transformer has 100 watts applied to its primary but only 90 watts available in the secondary. The efficiency of the transformer is ___________ %.
42. (90%)

TRANSFORMER APPLICATIONS

Transformers are versatile devices. They are used to step-up voltage, step-down voltage, step-up current, step-down current, and match impedance. Also, they can produce a 180° phase shift, provide two signals which are 180° out of phase, and isolate one circuit from another. They can pass AC while they block DC. They can also provide several signals at various voltage levels. You will now look at some of these applications in more detail.

Power Distribution

One of the most important applications of transformers is to transmit power over long distances. Often, the power generating stations are located near coal fields or dams which are usually far from the cities where the electrical power is needed. Therefore, the electrical energy must be transported over great distances by way of transmission lines. The transformer plays a major role in transmitting this energy efficiently.

Long distance transmission lines are generally made of aluminum. Copper lines have better electrical characteristics but are too expensive, too heavy, and lack structural strength. You will recall that aluminum has a higher resistivity than copper. Consequently, power losses in aluminum lines are high, unless special precautions have been taken.

Most of the power loss in a transmission line is caused by the resistance of the line. Recall that $P = I^2R$. Therefore, the amount of power loss is proportional to the resistance of the line and to the square of the current. Obviously then, the easiest way to reduce the power losses in the line is to keep the current as low as possible.

For example, suppose a generating station produces 12,000 volts at 10 amperes. Assume that this 120,000 watts of power are transmitted over a transmission line that has a resistance of 100 ohms. When transmitted as 12,000V at 10A, the power loss in the line is:

$$P = I^2R$$

$$P = (10A)2 \times 100 \text{ ohms}$$

$$P = 100 \times 100$$

$$P = 10{,}000 \text{ watts}$$

A transformer allows you to transmit the 120,000 watts as 120,000V at 1A. In this case, the power loss is:

$$P = I^2R$$

$$P = (1\ A)^2 \times 100\ \text{ohms}$$

$$P = 1 \times 100$$

$$P = 100\ \text{watts.}$$

Note that when you step the current down by a factor of 10, the power loss reduces by a factor of 100. For this reason, power is transmitted over great distances at very high voltage levels and very low current levels. Upon reaching its destination, the electrical power is stepped-down in voltage to the values required in homes and by industry.

Electronic Applications

In electronic devices, transformers are used to step-up or step-down voltage. Many electronic devices require 115 VAC for power. Most of the devices have a power transformer which steps the voltage up or down, as required. In transistorized and integrated circuit equipment, the AC line voltage is usually stepped-down and then changed to DC by a process called rectification. In older vacuum-tube equipment, the line voltage is usually stepped-up and then rectified. Vacuum tubes require higher DC voltages than transistors and integrated circuits. As you can see, you can use transformers to make the line voltage compatible with both types of equipment.

Transformers are also used as impedance-matching devices. They can match the impedance of one circuit to that of another. The impedances must be matched for maximum power to be transferred from one circuit to another circuit.

The above applications were described in detail earlier. Now, take a look at some additional applications.

PHASE SHIFTING

Depending upon how the transformer is wound, it provides either a 180° phase shift or no phase shift. This means that the voltage in the secondary is either in phase or 180° out of phase with the voltage in the primary.

In some applications, the phase shift is unimportant while in other applications it is extremely important. Figure 6-13A shows a transformer in which the input signal is in phase with the output signal.

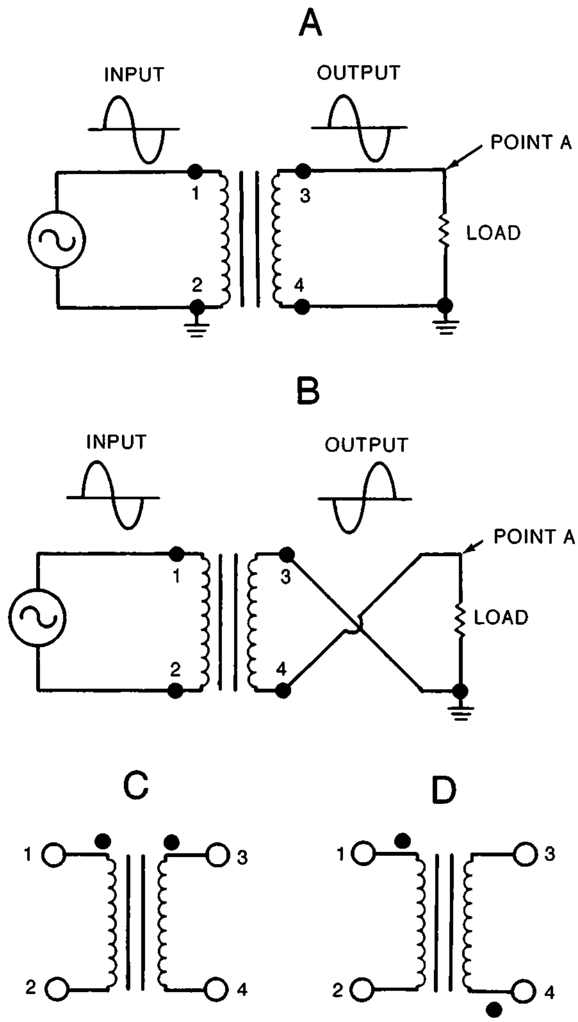


Figure 6-13
Phase relationships in transformers.

The voltage at point A with respect to ground has the same phase as the voltage at pin 1 with respect to ground. When you need a 180° phase shift between input and output, you can interchange the secondary's leads when you connect them to the load. Figure 6-13B shows the leads interchanged. Note that this places ground at pin 3 of the transformer. The voltage at point A is now 180° out of phase with the input voltage.

The phase relationship between the windings of the transformer are sometimes indicated on schematic diagrams by dots as shown in Figure 6-13C. The ends of the windings which are marked by dots are in-phase. Therefore, the voltage at

pin 3 is in phase with the voltage at pin 1. Figure 6-13D shows a transformer that is wound differently. Here, the voltage at pin 4 is in phase with the voltage at pin 1. Stated another way, the voltage at pin 3 is 180° out of phase with the voltage at pin 1.

Figure 6-14 shows that you can obtain an in-phase output or 180° out-of-phase output from either type of transformer. Note that you can reverse the phase simply by interchanging the leads to the load.

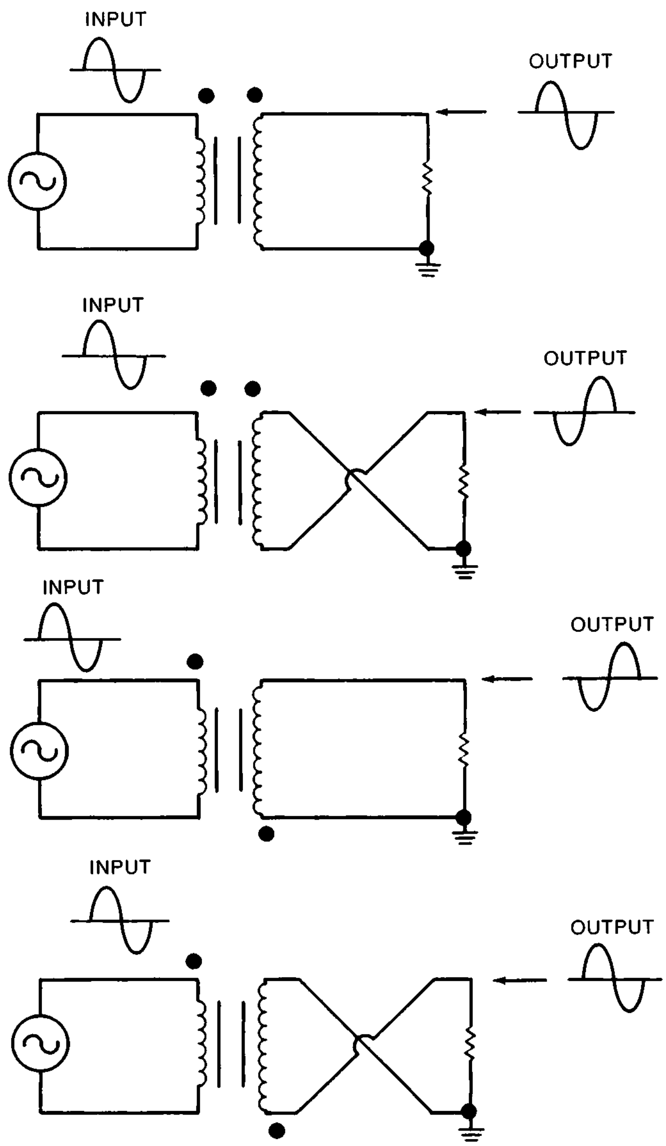


Figure 6-14
You can reverse the phase by interchanging the leads to the load.

PHASE SPLITTING

Some circuits require two AC signals of equal amplitude, but 180° out of phase. A transformer can be used to provide the two out-of-phase signals. Figure 6-15 shows a transformer with a center-tapped secondary. This simply means that the center of the secondary is brought out to a terminal which is labeled pin 4. In this Figure, the terminal is grounded. The dots indicate that the voltage at pin 3 is in phase with the voltage at pin 1. If you ignore the center tap, the voltage at pin 5 must be 180° out of phase with the voltage at pins 1 and 3. When the center tap is grounded, two signals which are equal in amplitude and 180° out of phase exist at the opposite ends of the secondary winding. Transformers are often used to produce two equal amplitude signals that are 180° out of phase.

Later in your study of electronic circuits, you will see this application used with audio amplifiers as part of a push-pull system.

ISOLATION

Another purpose of a transformer is to isolate one circuit from another. An AC device that does not use a power transformer often has a metal chassis that connects to one side of the AC power line. Anyone who touches this chassis and ground at the same time can receive an electrical shock. However, a power transformer isolates the chassis from the input AC line. When you separate the circuit from the input power, you greatly reduce the possibility of accidental shock.

Frequently, technicians must repair transformerless equipment. When the "hot" chassis is removed from its plastic or wooden cabinet, the possibility of accidental shock increases. To safeguard himself, the technician places an isolation transformer between the AC line and the chassis. The isolation transformer has a turns ratio of 1 to 1. That is, it takes 115 VAC from the line and delivers 115 VAC to the equipment. This isolates the chassis from the AC line and provides additional protection from accidental shock.

Autotransformer

An autotransformer is a special type of transformer. In the autotransformer, there is no isolation between the primary and the secondary windings. A single continuous coil is wound on a core. Part of this coil is used as the primary, while another part is used as the secondary. Generally, part of the coil is used as both primary and secondary.

Figure 6-16A shows an autotransformer being used to step-down the applied voltage. Here, the entire winding serves as the primary. The lower half of the coil is used as the secondary winding. Because there are fewer turns in the secondary than in the primary, the voltage is stepped-down and the current is stepped-up.

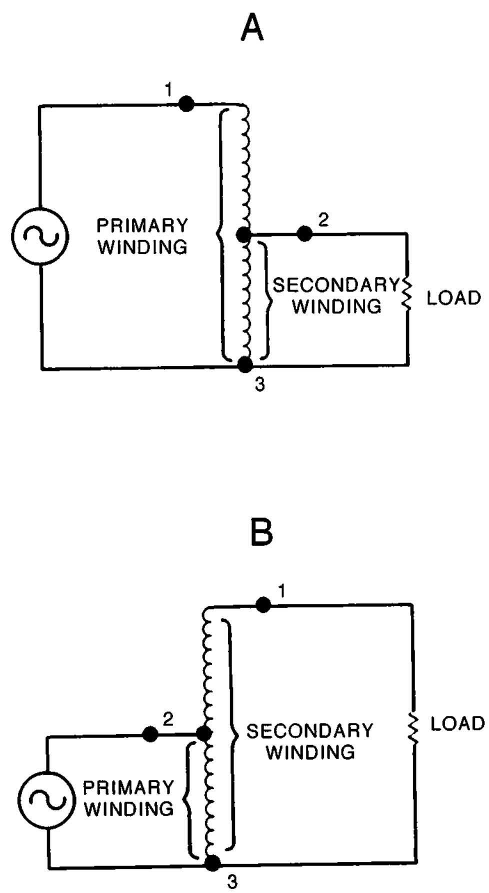


Figure 6-16
An autotransformer.

Figure 6-16B shows that you can turn the transformer around to step-up voltage. Here, the lower half of the coil is used as the primary while the entire coil is used as the secondary. Since the secondary has more turns, the transformer steps-up voltage and steps-down current.

Figure 6-17 compares the autotransformer with a conventional transformer. The conventional transformer in Figure 6-17A steps the applied voltage down from 120 VAC to 20 VAC. This requires a turn ratio of 6:1. If you ignore losses, the current steps-up from 1A to 6A.

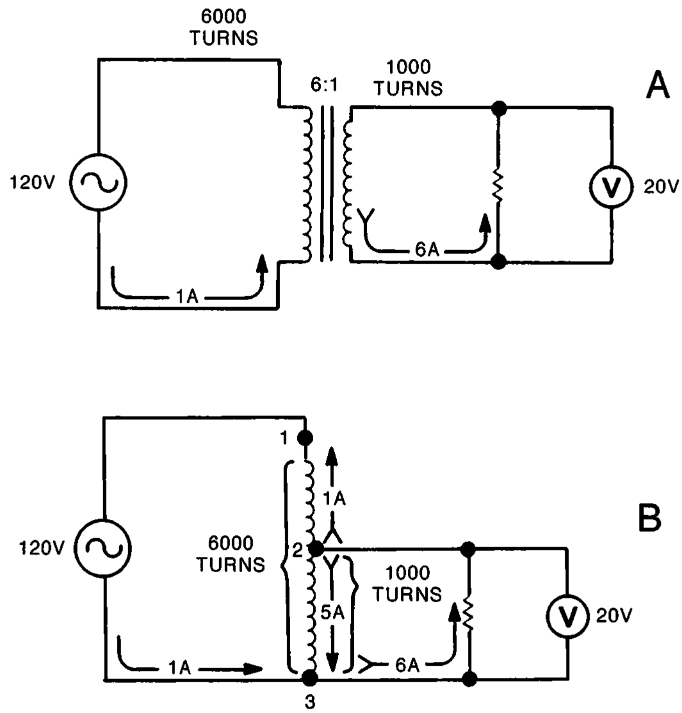


Figure 6-17
Comparing an autotransformer
to a conventional transformer.

Figure 6-17B shows how you can accomplish the same job with an autotransformer. The tap at pin 2 is placed at 1,000 turns. Thus, the primary, in this case the entire coil, has 6,000 turns. Only 1,000 of the turns are used for the secondary. Note that 6 amperes flows in the load, but only 5 amperes flows through the secondary winding. The reason for this is that the current in the secondary winding flows in the opposite direction to the current flowing in the primary. Thus, the 1 ampere primary current subtracts from the 6 amperes of secondary current.

This illustrates the advantages of an autotransformer. First note that fewer turns of wire are required in an autotransformer. Also, since the current in the secondary winding is lower, the I^2R loss is lower. In many cases, the autotransformer is also easier to construct and therefore less expensive. Its main disadvantage is that the secondary is not isolated from the primary. It is usually used in electronic circuits that have low-current and high-frequency requirements.

A special type of autotransformer is shown in Figure 6-18. The load is connected between the movable arm and the bottom of the coil. You can move the arm up or down to change the turns ratio. This causes a corresponding change in voltage across the load. You can vary the output voltage from about 0 VAC to over 130 VAC. This device is called a variable autotransformer.

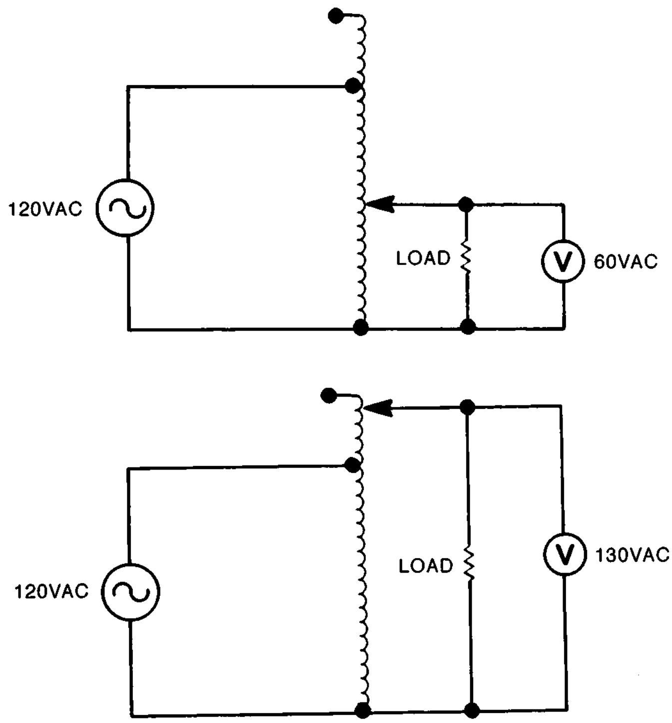


Figure 6-18
The variable transformer.

The autotransformer gets its name because it is usually used in the audio frequency range. The audio frequency range is considered to extend from approximately 10 hertz to 25,000 hertz.

Due to their inductive reactance, transformers have limited uses in high-frequency circuits. The exception is the special tuned tanks in IF and RF applications. These special signal-coupling transformers are used in extremely low-current applications. This coupling requirement is usually in the microampere range.

Programmed Review

43.	When power is transmitted over long distances, the current is kept as low as possible. This minimizes ___________ losses in the transmission lines.
44.	(power or I^2R) In electronic applications, transformers are used to change current levels, change voltage levels, and match ___________ .
45.	(impedance) A transformer can produce a phase shift of 0° or ___________°.
46.	(180°) A center-tapped secondary produces two voltages which are ___________° out of phase.
47.	(180°) A transformer which consists of a single continuous tapped winding is called an ___________ .
48.	(autotransformer) The disadvantage of an autotransformer is that it does not provide ___________ between the input and the output circuits.
49.	(isolation)

EXPERIMENT 10

Transformer Characteristics

OBJECTIVES: *To examine the construction of a transformer and measure the DC resistance of its windings.*

To calculate the turns ratio of a transformer.

To determine whether or not a transformer is a step-up or step-down transformer.

To evaluate the effect of loading a transformer.

To demonstrate how a transformer can be used as an autotransformer.

To explain several transformer applications.

Introduction

A small audio transformer is provided with this course. You can use it to verify some of the principles that were discussed in this unit. However, one of the first things you will learn about this transformer is that it is by no means ideal. Its efficiency is low and its AC resistance is high. This can cause some confusing results unless you take these factors into consideration.

Materials Required

Heathkit Analog Trainer
Oscilloscope
Multimeter
1—Audio Transformer (#51-97)
1—1000 Ω, 1/2-watt resistor (brown-black-red)
1—100 Ω, 1/2-watt resistor (brown-black-brown)

Procedure

1. Find the audio transformer (#51-97) and examine its construction. Note that it has a laminated core that is made up of E and I laminations. The primary and secondary are wound on a nylon bobbin around the center arm of the E laminations. The windings consist of several hundred turns of very fine copper wire. They are covered by a layer of tape for protection.

2. Refer to Figure 6-19A and identify the five leads on the transformer. Write the proper number of each pin on the protective tape immediately above the terminals.

3. Refer to Figure 6-19B. Compare this schematic diagram of the transformer with the actual transformer.

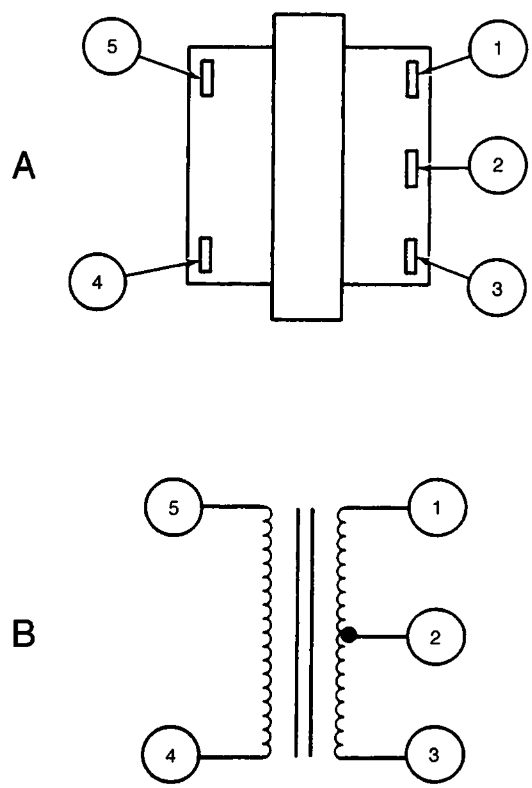


Figure 6-19
Identification of transformer leads.

4. Refer to Figure 6-20A. Use an ohmmeter to measure the DC resistance of the winding between pins 4 and 5. Call this resistance $R_{4,5}$. $R_{4,5}$ = __________ ohms.

5. Measure the resistance between pins 1 and 3 as shown in Figure 6-20B. $R_{1,3}$ = __________ ohms.

6. Measure the resistance between pins 1 and 2 as shown in Figure 6-20C. $R_{1,2}$ = __________ ohms.

7. Measure the resistance between pins 2 and 3 as shown in Figure 6-20D. $R_{2,3}$ = __________ ohms. Does $R_{2,3}$ equal $R_{1,2}$? ________ What assumption can you make about the position of the tap which connects to pin 2?
____
____.

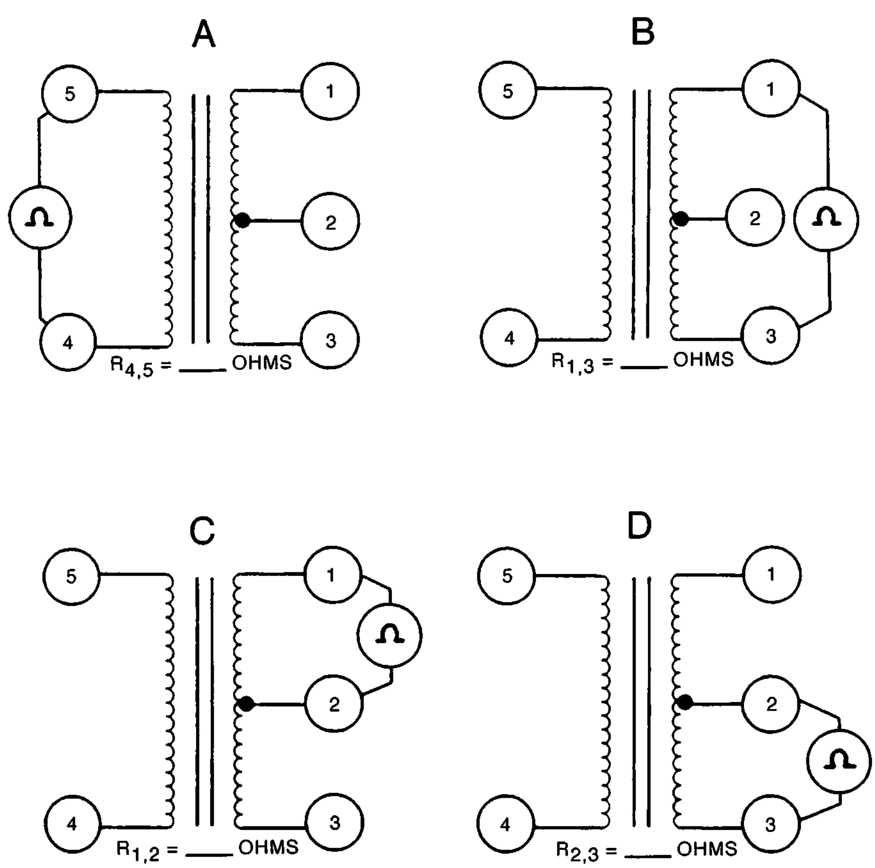


Figure 6-20
Measure the DC resistance of each winding.

Discussion

In this part of the experiment, you examined the construction of the transformer and measured the DC resistance of its winding. Typical DC resistance values are:

$$R_{4,5} = 700 \text{ ohms}$$

$$R_{1,3} = 100 \text{ ohms}$$

$$R_{1,2} = 50 \text{ ohms}$$

$$R_{2,3} = 50 \text{ ohms}$$

Since $R_{1,2}$ and $R_{2,3}$ are equal, pin 2 must be at the center of the winding between pins 1 and 3.

Keep in mind that these are the DC resistance values. The AC resistance of these windings will be even higher. Thus, when you experiment with a transformer, you must remember that these resistance values exist. That is, it is sometimes necessary to think of the transformer as shown in Figure 6-21. Here R_A represents the AC resistance between pins 4 and 5. This value may be somewhat larger than $R_{4,5}$. In the same way, R_B represents the AC resistance between pins 1 and 2 while R_C represents the AC resistance between pins 2 and 3.

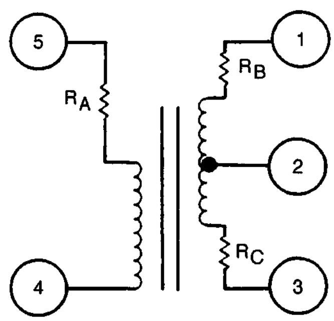


Figure 6-21
The AC resistance of the windings act like series-dropping resistors.

These AC resistance values are aggravating for several reasons. They are difficult to measure directly. They also interfere with the operation of the transformer and waste power. Finally, they change somewhat with frequency. You must keep these AC resistances in mind while you continue the experiment.

Procedure (continued)

8. Cut five 3-inch lengths of hook-up wire. Strip 1/4 inch of insulation from each end of each wire. Solder one wire to each of the five pins on the transformer.

9. Use the Trainer to connect pins 4 and 5 of the transformer across the 15 VAC LINE FREQ terminals as shown in Figure 6-22A. Leave pins 1, 2, and 3 open.

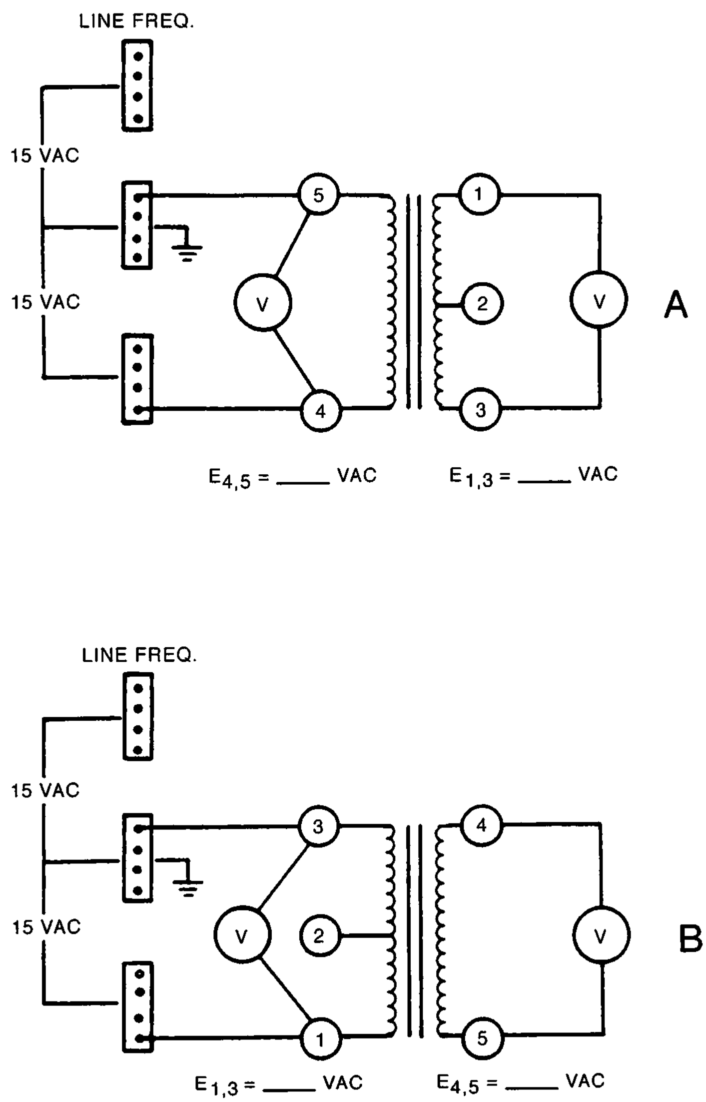


Figure 6-22
The transformer can be used
to step-up or step-down voltage.

10. Place your voltmeter on an AC voltage range greater than 15 VAC and measure the applied voltage between pins 4 and 5. $E_{4,5}$ = __________ VAC. Is the winding between pins 4 and 5 being used as a primary or as the secondary? ________________.

11. Move your voltmeter to pins 1 and 3. $E_{1,3}$ = __________ VAC. Is the winding between pins 1 and 3 being used as a primary or as a secondary? ________________.

12. Compare the primary voltage with the secondary voltage. Is the applied voltage being stepped-up or stepped-down? ________________.

13. Use the following formula to determine the primary-to-secondary turns ratio of the transformer:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

Turns ratio = __________:1.

14. Disconnect the transformer from the Trainer. Connect pins 1 and 3 across the 15 VAC LINE FREQ terminals as shown in Figure 6-22B. Leave pins 2, 4, and 5 open.

15. Measure the applied voltage. $E_{1,3}$ = __________ VAC. In this case, the winding between pins 1 and 3 is the ______________.
primary/secondary

16. Measure the voltage between pins 4 and 5. $E_{4,5}$ = __________ VAC. The winding between pins 4 and 5 is the ______________ VAC.
primary/secondary

17. Compare the primary voltage with the secondary voltage. Is the applied voltage being stepped-up or stepped-down? ______________.

18. Use the following formula to determine the secondary-to-primary turns ratio of the transformer:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

Turns ratio = __________:1.

19. Does this turns ratio agree with your computation earlier in step 13? ___________. Which winding has more turns, the one between pins 4 and 5 or the one between pins 1 and 3? ____________________________.

Discussion

In steps 9 through 13 you used the transformer to step-down the applied voltage. By definition, the primary of the transformer is the winding to which a voltage is applied from an outside source. Thus, the winding between pins 4 and 5 is the primary. Typically, the applied voltage, $E_{4,5}$ is 17 VAC. This gives a secondary voltage, $E_{1,3}$ of about 7 VAC. Note that the applied voltage is stepped-down from 17 VAC to 7 VAC. With the formula given in step 13, the turns ratio is approximately:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{17\text{ VAC}}{7\text{ VAC}} = \frac{N_P}{N_S} = 2.43$$

Because the voltage is stepped-down, the primary must have more turns than the secondary. That is, the winding between pins 4 and 5 must have about 2.43 times as many turns as the winding between pins 1 and 3.

In steps 14 through 19, you turned the transformer around and used the winding between pins 1 and 3 as the primary. Here $E_{1,3}$ is about 17 VAC while $E_{4,5}$ is about 40 VAC. The voltage is stepped-up from 17 VAC to 40 VAC. This gives a turns ratio of:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

$$\frac{40\text{ VAC}}{17\text{ VAC}} = \frac{N_S}{N_P} = 2.35$$

That is, the secondary has 2.35 times as many turns as the primary.

These examples show you that you can step-up or step-down a voltage by a factor of about 2.4. This is possible because one winding has about 2.4 times as many turns as the other. The turns ratio is fixed and cannot be changed. However, you can use only half of the winding between pins 1 and 3 to double the turns ratio.

Procedure (continued)

20. Connect pins 1 and 2 across the 15 VAC LINE FREQ terminals on the Trainer as shown in Figure 6-23A. Leave pins 3, 4, and 5 open.

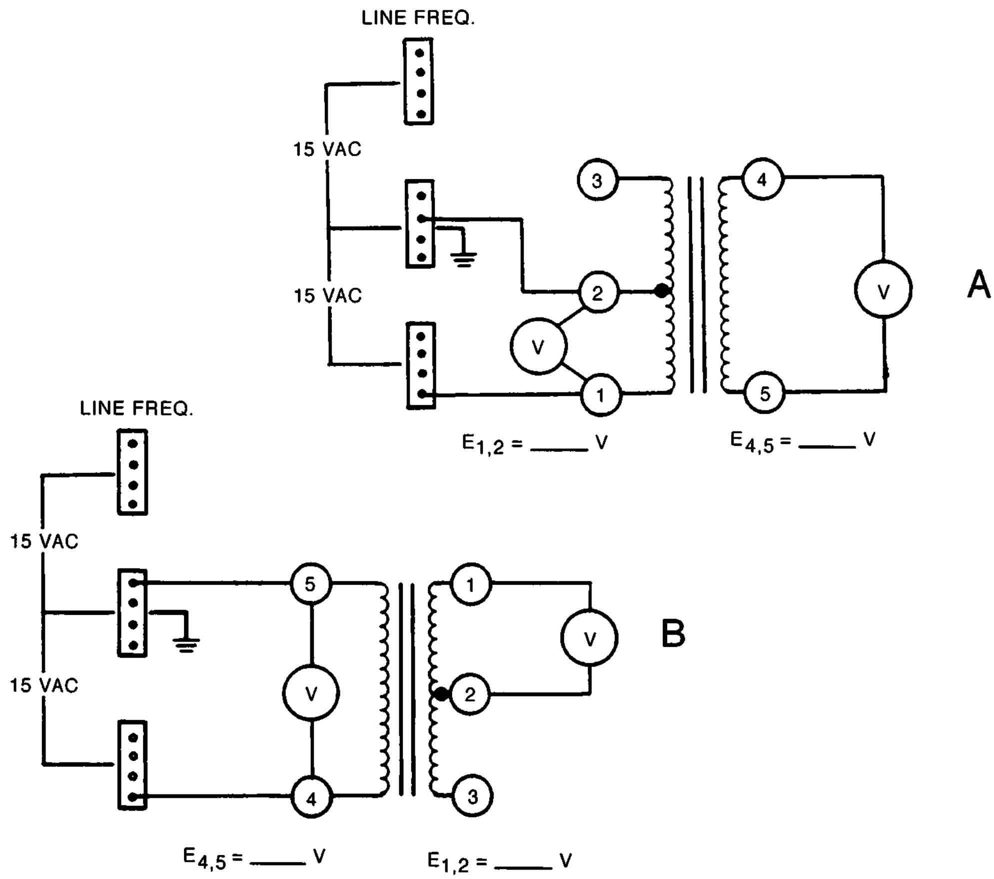


Figure 6-23
The turns ratio is doubled with only one half of the tapped winding.

21. Measure the voltage between pins 1 and 2. $E_{1,2}$ = __________ VAC.

22. Use the 100 VAC range on your meter to measure the voltage between pins 4 and 5. $E_{4,5}$ = __________ VAC. Is the voltage stepped-up or down? ________.

23. Compute the turns ratio. The winding between pins 4 and 5 has ___________ times as many turns as the winding between pins 1 and 2.

24. Disconnect the transformer from the Trainer. Connect pins 4 and 5 across the 15 VAC LINE FREQ terminals on the Trainer as shown in Figure 6-23B. Leave pins 1, 2 and 3 open.

25. Measure the voltage between pin 1 and 2. $E_{1,2}$ = ___________ VAC. Is the applied voltage stepped-up or down? _______________.

26. Compute the turns ratio. The winding between pins 4 and 5 has ___________ times as many turns as the one between pins 1 and 2.

Discussion

In these examples, you using only one half of the center tapped winding to double the turns ratio. In step 21, $E_{1,2}$ is about 22 VAC. $E_{4,5}$ is about 54 VAC. Thus, the turns ratio is:

$$\frac{54\text{ VAC}}{22\text{ VAC}} = 2.5$$

Next, you turned the transformer around to step the 22 VAC down to about 3.5 VAC. This produces a turns ratio of about 6.29 to 1. Note that in each case, the turns ratio is about twice the value you computed earlier.

The losses in the transformer did not interfere very much with the measurements you made up to this point. The reason for this is that the secondary has been unloaded except for the high impedance of the voltmeter. Normally though, a transformer has a secondary load. This increases both secondary and primary current. When current flows, the losses in the transformer become obvious.

Procedure (continued)

27. Use the transformer and a 1000 Ω resistor to connect the circuit shown in Figure 6-24A. Leave pins 1, 2, and 3 open.

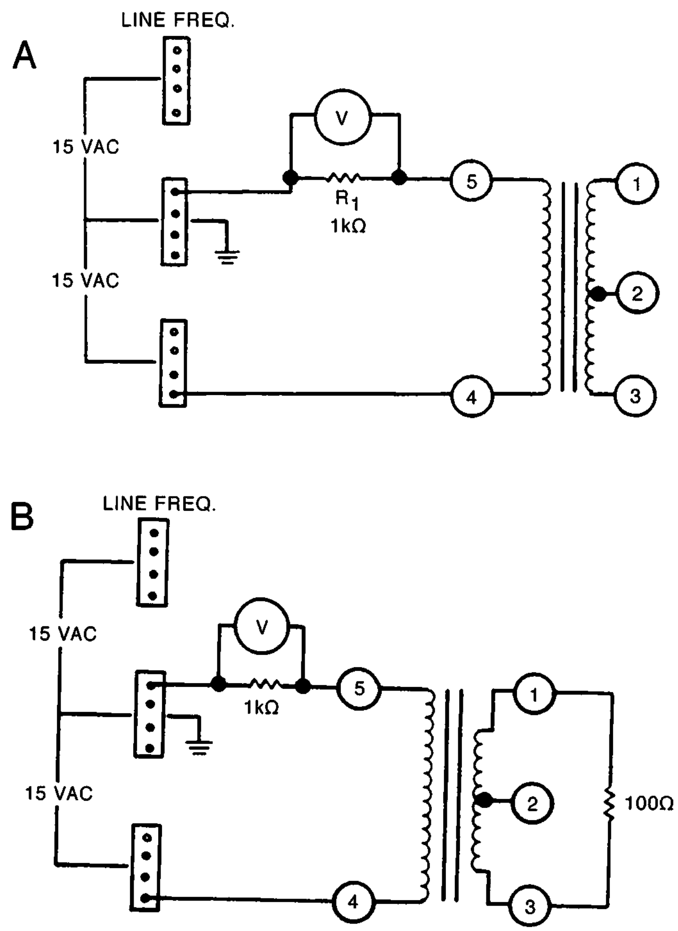


Figure 6-24
Loading the secondary increases the current in the primary.

28. Be sure that you observe polarity and measure the voltage across R_1. E_{R1} = ___________ V. Use Ohm's Law to find the current in the primary.

$$I_P = \frac{E_{R1}}{R_1} = \frac{\qquad}{1000} = \_\_\_\_\_\_\_\_\_\_ \text{ amperes}$$

or ___________ milliamperes Because the secondary has no load, this current is called the ___________ current.

29. Load the secondary by connecting a 100-ohm resistor (R_2) between pins 1 and 3. Now what is the voltage drop across R_1? E_{R1} = __________ V. Use Ohm's Law to find the current in the primary.

$$I_P = \frac{E_{R1}}{R_1} = \frac{\quad}{1000} = \_\_\_\_\_\_\_\_\_\_ \text{ amperes or } \_\_\_\_\_\_\_\_\_\_ \text{ mA}$$

What happens to the primary current when the secondary is loaded? ______________________________.

30. Measure the voltage between pins 4 and 5 of the transformer. $E_{4,5}$ = __________ V.

31. Measure the voltage between pins 1 and 3 of the transformer. $E_{1,3}$ = __________ V.

32. Use the values you measured in steps 30 and 31 to determine the turns ratio. Turns ratio = __________. Does this agree with the value you computed in step 13? __________. Does the turns ratio formula work when the transformer is loaded? __________ Why? ______________________________.

33. Use Ohm's Law to determine the current in the secondary.

$$I_S = \frac{E_{1,3}}{100\ \Omega} = \_\_\_\_\_\_\_\_\_\_ \text{ A or } \_\_\_\_\_\_\_\_\_\_ \text{ mA}$$

34. Is the voltage stepped up or down? ______________.

Is the current stepped up or down? ______________.

Discussion

In step 28, you computed the exciting current of the transformer. A typical value is 0.7 mA. Next, you loaded the secondary and verified that the primary current increased. Typically, the primary current increases to about 5.8 mA. This demonstrates that a decrease in secondary impedance causes a decrease in primary impedance. This effect is sometimes referred to as reflected impedance.

In the next steps, you demonstrated that the turns ratio formulas are not very accurate when the transformer is loaded. One reason for this is that the AC resistance of the windings interferes with the voltmeter readings. For example, in step 30 you measured the voltage between pins 4 and 5. It might seem that this is the

primary voltage E_P. However, strictly speaking, it is not. Rather it is the vector sum of the primary voltage (E_P) and the voltage dropped by the AC resistance of the primary winding. E_P is actually somewhat smaller than this value. A similar effect occurs in the secondary. Thus, the voltage readings you took in steps 30 and 31 are not accurate measurements of E_P and E_S. Consequently, the turns ratio you computed with these values may be very inaccurate.

A previous section briefly described the autotransformer. While the device provided with this course is not an autotransformer, you can use it to demonstrate some of the characteristics of an autotransformer.

Procedure (continued)

35. Connect pins 1 and 2 of the transformer across the 15 VAC LINE FREQ terminals as shown in Figure 6-25A. Be sure that pin 1 is connected to the ground terminal. Leave pins 3, 4, and 5 open. If you ignore the winding between pins 4 and 5, you can think of the remaining winding as an autotransformer.

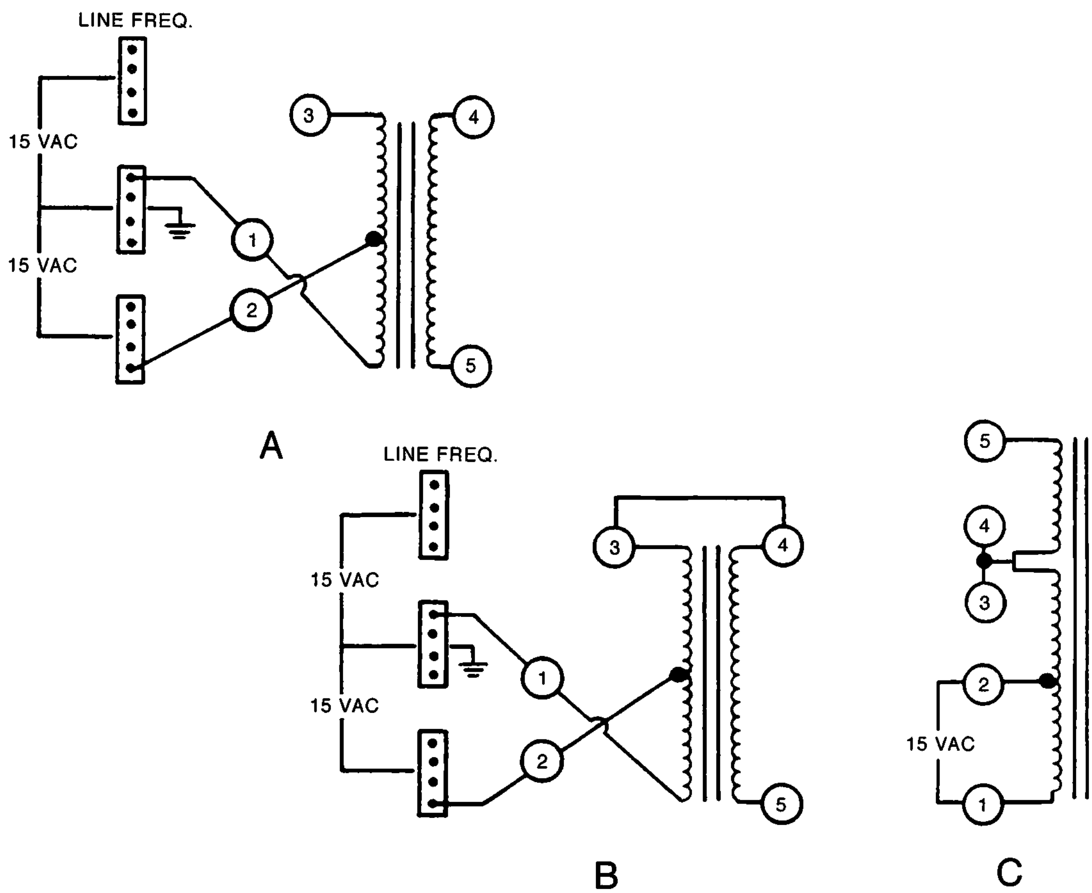


Figure 6-25
The principles of an autotransformer.

36. The voltage is applied between pins 1 and 2. Thus, the winding between pins 1 and 2 is the ___________ winding. $E_{1,2}$ = ___________ VAC.

37. The output voltage is taken between pins 1 and 3. Thus, the winding between pins 1 and 3 is the ___________ winding. Which has more turns, the secondary winding or the primary winding? ___________. Therefore, $E_{1,3}$ should be ___________ than $E_{1,2}$.
    higher/lower

    Measure $E_{1,3}$. $E_{1,3}$ = ___________ VAC.

38. You can include the unused winding between pins 4 and 5 in the makeshift autotransformer. Connect pins 3 and 4 of the transformer as shown in Figure 6-25B.

39. Measure and record the following values:

    E1,2 = ___________ VAC.
    E1,3 = ___________ VAC.
    E1,4 = ___________ VAC.
    E1,5 = ___________ VAC.

Discussion

In step 35 you connected the transformer as a simple autotransformer. The winding between pins 1 and 2 is the primary while the winding between pins 1 and 3 is the secondary. Naturally, there are more turns between pins 1 and 3 than between pins 1 and 2. In fact there are twice as many. Therefore, $E_{1,3}$ should be about twice the value of $E_{1,2}$. In step 38, the autotransformer is expanded to include the winding between pins 4 and 5. Recall that this winding has approximately 2.4 times as many turns as that between pins 1 and 3. The winding between pins 1 and 2 is still used as the primary. Thus, the voltage between pins 1 and 5 should be considerably higher than the applied voltage. Figure 6-25C shows the schematic diagram of the transformer connected as if it were an autotransformer.

SUMMARY

The transformer is a device that couples AC signals from one circuit to another.

During the transformation process, the voltage or the current may change. However, the frequency never changes.

A transformer consists of two or more windings that are wound on a core. The winding to which an input signal is applied is called the primary. The winding from which an output signal is taken is called the secondary. The core material is usually air, steel, soft iron, or silicon steel. Metal cores have a high permeability that increases magnetic flux density.

Transformer action is based upon electromagnetic mutual inductance. Current in the primary produces a magnetic field which induces an EMF into the secondary. In turn, secondary current produces a magnetic field which induces an EMF into the primary. This EMF opposes the counter EMF of the primary. Consequently, an increase in secondary current causes an increase in primary current. When the secondary is open, an excitation current still flows in the primary winding.

The voltage ratio, the current ratio, and the impedance ratio of a transformer is determined by the turns ratio. Turns ratio is the number of turns in the primary compared to the number of turns in the secondary. Voltage and impedance are directly proportional to the turns ratio, and current is inversely proportional to the turns ratio.

The formula for the turns ratio is:

$$\text{Turns ratio} = \frac{N_S}{N_P}$$

The formula for the voltage ratio is:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P} \quad \text{or} \quad \frac{E_P}{E_S} = \frac{N_P}{N_S}$$

The formula for the current ratio is:

$$\frac{I_S}{I_P} = \frac{N_P}{N_S} \quad \text{or} \quad \frac{I_P}{I_S} = \frac{N_S}{N_P}$$

The formulas which use turns ratios assume that the transformer is ideal (has no losses). This is the same as assuming that the transformer is 100% efficient. Since all transformers have losses, their efficiencies are less than a 100%. However, 90% efficient is considered to be the norm.

You can use a transformer to match the impedance of one circuit to that of another. This is important since maximum power is transferred only when the impedance of the source matches that of the load.

The impedance formula is:

$$\frac{Z_P}{Z_S} = \left(\frac{N_P}{N_S}\right)^2 \quad \text{or} \quad \frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}$$

Transformer losses consist primarily of core losses and copper losses. Core losses are caused by eddy currents and hysteresis. Many transformer cores are laminated to reduce eddy current losses. Copper losses are caused by the AC resistance of the transformer's windings. Small values of current keep hysteresis losses low. You can use the following formula to determine the efficiency of a transformer:

$$\%\ \text{efficiency} = \frac{P_S}{P_P} \times 100$$

Some applications of transformers include:

- Stepping-up voltage
- Stepping-down voltage
- Stepping-up current
- Stepping-down current
- Impedance matching
- Providing a 180° phase shift
- Providing two signals which are 180° out-of-phase
- Isolating one circuit from another
- Passing AC, but blocking DC

An autotransformer is a special type transformer which consists of a continuous winding on a core. You can use it like any other transformer except that it does not provide isolation between the input and output. Autotransformers are usually used in the audio frequency range, which is between 10 hertz and 25 kilohertz.

An isolation transformer is a special purpose transformer that is used to isolate one circuit from another. Frequently, technicians use a 1:1 isolation transformer to isolate a transformerless chassis from the AC line.

UNIT EXAMINATION

The following multiple choice examination is designed to test your understanding of the material presented in this unit. Place a check beside the multiple choice answer (A, B, C, or D) that you feel is most correct. After you complete the examination, compare your answers with the correct ones that appear in the Examination Answer Sheet which follows.

1. What turns ratio is required to match a 400-ohm generator to a 16-ohm load?

   A. 400 to 1
   B. 25 to 1
   C. 16 to 1
   D. 5 to 1

2. The losses which are created by the AC resistance of the windings in a transformer are called:

   A. hysteresis losses.
   B. eddy current losses.
   C. copper losses.
   D. stray losses.

3. Many transformers have laminated cores in order to minimize:

   A. hysteresis losses.
   B. eddy current losses.
   C. copper losses.
   D. stray losses.

4. A transformer which has more turns in the secondary than in the primary:

   A. steps-up voltage.
   B. steps-up current.
   C. steps-down voltage.
   D. steps-up power.

5. A transformer has 2000 turns in the primary and 400 turns in the secondary. The primary voltage is 100 VAC. Ignoring losses, what is the secondary voltage?

   A. 100 VAC
   B. 20 VAC
   C. 2000 VAC
   D. 5 VAC

6. A transformer has 1000 primary turns and 4500 secondary turns. The secondary current is 10 mA. Ignoring losses, what is the primary current?

A. 45 mA
B. 2.22 mA
C. 10 mA
D. 450 mA

7. A transformer has 72 watts in the primary and 64 watts in the secondary. What is the efficiency?

A. 80%
B. 89%
C. 72%
D. 112.5%

8. A transformer consists of one continuous winding with several taps so you can take off different voltages. This type of transformer is called:

A. an isolation transformer.
B. a power transformer.
C. a current transformer.
D. an autotransformer.

9. When the impedance connected across the secondary winding of a transformer decreases:

A. both primary and secondary currents increase.
B. both primary and secondary currents decrease.
C. primary current increases, secondary current decreases.
D. primary current decreases, secondary current increases.

10. A transformer has a turns ratio of 1:1. What is this transformer used for?

A. impedance matching
B. changing frequency
C. isolation
D. stepping-up voltage

EXAMINATION ANSWERS

1. D— $\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}$

$$\frac{N_P}{N_S} = \sqrt{\frac{400}{16}}$$

$$\frac{N_P}{N_S} = \sqrt{25}$$

$$\frac{N_P}{N_S} = 5$$

2. C —The losses which are caused by the AC resistance of the windings of the transformer are called copper losses.

3. B — Laminated cores are used to minimize eddy current losses.

4. A —A transformer with more turns in its secondary than in its primary is used to step-up voltage.

5. B — $\frac{E_P}{E_S} = \frac{N_P}{N_S}$

$$\frac{100\text{ V}}{E_S} = \frac{2000}{400}$$

$$\frac{100\text{ V}}{E_S} = \frac{5}{1}$$

$$5\,E_S = 100\text{ V}$$

$$E_S = 20\text{ V}$$

6. A —Ignoring losses:

$$\frac{I_P}{I_S} = \frac{N_S}{N_P}$$

$$\frac{I_P}{10 \text{ mA}} = \frac{4500}{1000}$$

$$I_P = \frac{4500}{1000} \times 10 \text{ mA}$$

$$I_P = 45 \text{ mA}$$

7. B —% efficiency = $\frac{P_S}{P_P} \times 100$

$$= \frac{64}{72} \times 100$$

$$= .8888 \times 100$$

$$= 88.88\% \text{ or } 89\%$$

8. D —The autotransformer has one continuous winding.

9. A —When the impedance in the secondary decreases, both the primary and the secondary currents increase.

10. C —The isolation transformer has a 1:1 ratio.

UNIT 7

MOTORS AND MOTOR CONTROLS

CONTENTS

INTRODUCTION

In this unit you will learn about the basic differences between motors, basic motor control components, and motor control systems. This unit is designed to introduce you to motors, motor terminology, and to motor's principles of operation. The types of motors and controls explained in this unit are the types that you will encounter both in your home and in industrial applications.

This unit combines what you learned about resistors, inductive and capacitive principles, and electromagnetic induction principles in DC and AC electronics into practical circuits.

To begin this unit, you will review electromagnetic induction, generators, and DC motors.

UNIT OBJECTIVES

When you complete this unit you will be able to:

1. Define the term motor.
2. Demonstrate the right-hand rule for motors.
3. Explain the principle of electromagnetic induction.
4. Explain the operation of the following types of motors: series type, shunt type, and compound type.
5. Draw the waveform for a single-phase motor.
6. Name the common use for a two-phase motor.
7. Explain the phase relationships between the windings of a three-phase motor.
8. Calculate the percent of regulation for a motor when you know the loaded and unloaded operating speed.
9. Explain the relationship between the magnetic field strength and RPM.
10. State the type of motor that is called a universal motor.
11. Explain the relationship between a motor's slippage and its torque.
12. Define the motor terms inertia and friction.
13. Draw a DC control circuit that can reverse a motor's direction and change its speed of operation.
14. Use a schematic diagram to differentiate between a servo system and a synchro system.
15. Define the terms synchronous and asynchronous as they apply to motors.
16. Explain the relationship between torque and synchronous and asynchronous motors.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "Review of DC Motors."	________
☐ Complete Programmed Review Frames 1-6.	________
☐ Read "Types of Induction Motors."	________
☐ Complete Programmed Review Frames 7-15.	________
☐ Read "AC Motors."	________
☐ Complete Programmed Review Frames 16-29.	________
☐ Read "Motor Speeds."	________
☐ Complete Programmed Review frames 30-41.	________
☐ Read "Motor Control Circuits."	________
☐ Complete Programmed Review Frames 42-55.	________
☐ Perform Experiment 11: Identifying Motor Symbols.	________
☐ Study the Summary.	________
☐ Complete the Unit Examination.	________
☐ Check the Examination Answers.	________

REVIEW OF DC MOTORS

In your study of DC Electronics, you saw that a generator converts mechanical energy into electrical energy. A DC motor does just the opposite: it converts electrical energy to mechanical energy. Figure 7-1 illustrates the principle that makes this conversion possible. In the figure, a current-carrying conductor is shown in a magnetic field. This current is not induced. Instead the current flows because the conductor is connected to a battery. This current causes a magnetic field to develop around the conductor in the direction shown. You can verify this with the left-hand rule for conductors.

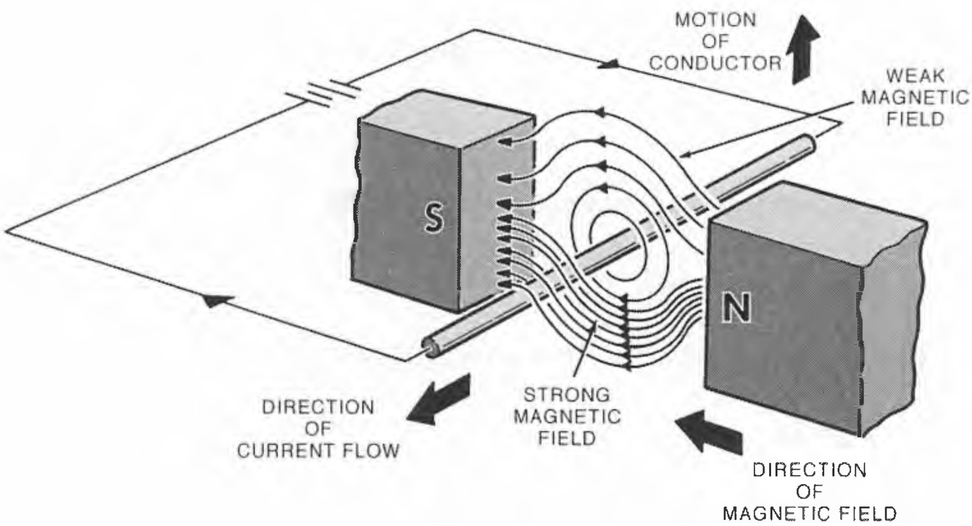


Figure 7-1
DC motor theory.

Induction Principles

In the figure, the magnetic field around the conductor interacts with the field of the permanent magnet. On one side of the conductor, the two magnetic fields are in the same direction and they add. This aiding magnetic field produces a strong magnetic field. On the other side of the conductor, the two magnetic fields are in opposite directions. Opposing magnetic fields tend to cancel each other, which results in a weak magnetic field.

As you can see in Figure 7-1, the flux lines are more numerous on one side of the conductor than on the other. Thus, on one side, the lines are bent and forced very close together. These lines have a natural tendency to straighten and move farther apart. However, the only way they can do this is to push the conductor out of the way. Thus, a force develops that pushes the conductor in the direction shown.

The rule which determines the direction that the conductor will move in the magnetic field is called the right-hand motor rule. The right-hand rule is illustrated in Figure 7-2. With your right hand, point your index finger in the direction of the field of the permanent magnet. Point your middle finger in the direction of current flow through the conductor and at a right angle to the index finger. Point your thumb straight up and at a right angle to both the index and middle fingers. Your thumb now points in the direction that the conductor will move. When you apply this rule, you can see how a simple DC motor operates.

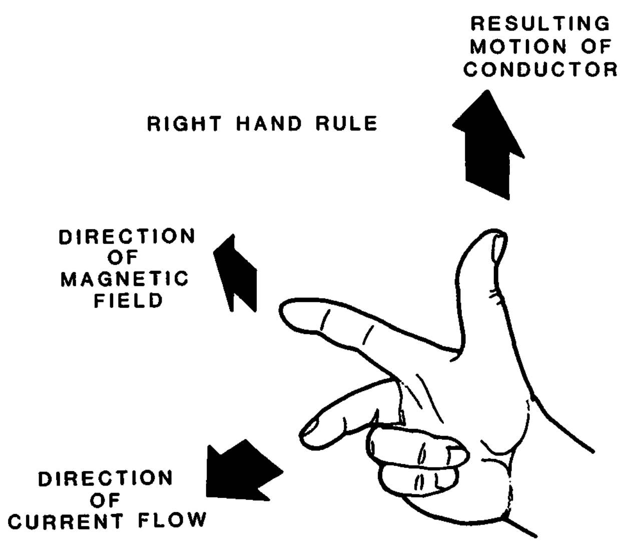


Figure 7-2
Rule for motor action.

A simplified drawing of a DC motor is shown in Figure 7-3. This is similar to the DC generator that was described earlier. However, there are two important differences between generators and motors. First, with the generator the armature is turned by an outside mechanical force. However, in a motor the armature turns due to the electrical force that is applied. Second, in the generator a DC voltage is picked off the armature by the brushes. In a motor, an external DC voltage is applied to the brushes.

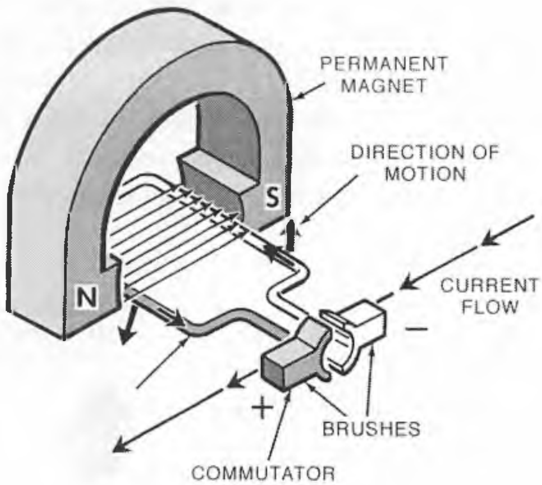


Figure 7-3
The DC motor.

Right-Hand Motor Rule

Current flows through the armature as indicated by the arrows in Figure 7-1. If you apply the right-hand motor rule to the side of the armature near the south pole of the magnet, you find that the conductor tends to move up. When you apply the same rule to the side near the north pole, you find that this side tends to move down. Thus, the armature rotates in a counterclockwise direction. After one half cycle of revolution, the two sides of the armature interchange positions. Nevertheless, current still flows in the same direction and through the side closest to the south pole. Whichever side of the armature appears at this point, the resulting motion is always up. The upward force at the south pole and the downward force at the north pole causes the armature to rotate.

The motor shown in Figure 7-3 is not practical because the armature consists of a single loop of wire. Motors use hundreds of turns of wire in the armature winding. Many conductive wires for the armature cause a very strong twisting motion, or *torque*, to be developed. The single loop demonstrates what happens due to motor action. The many loops in the armature all operate on this principle and they are additive (aiding).

Small DC motors are rated in fractional horsepower (HP). Fractional horsepower motors are usually operate with a split-phase winding, which means the single winding is divided into a start and a run section. The primary advantage of the DC motor is its simplicity of design and flexibility. Its primary disadvantage is its tendency to run away under no-load conditions.

DC Motor Problems

The most common cause of a malfunction in DC motors is brush related. Therefore, you should visually inspect the brushes for wear, spring tension, and arcing as part of a periodical inspection phase. As the brush wears, it deposits conductive dust inside the motor housing. This dust can accumulate and cause short circuits. To save money and time, replacing the brushes before they damage the armature. Brushes are relatively inexpensive and armatures are very expensive. When you periodically inspect and service motors, are they don't cause as many unscheduled shut downs as they do when you service them only when they malfunction.

Many motors require periodic lubrication. Lubrication prevents excessive surface wear on the motor's bearings and the armature's shaft. You should use care not to use excessive amounts of lubrication. Excessive oil or grease can trap dirt and foreign materials which could increase friction or cause shorts. Some lubrication materials are nonconductive and if you allow them to get onto the armature could rub off on the brush face and insulate the brush from the armature's surface.

Programmed Review

1.	With the right-hand motor rule, your thumb points in the direction of the ___________ ___________ .
2.	(conductor motion) The twisting force that is applied to a motor is defined as ___________ .
3.	(torque) The advantages of DC motors when compared to AC motors are their simplicity of design and ___________ .
4.	(flexibility) One serious disadvantage of a DC series motor under no-load conditions is its tendency to _________ _________ .
5.	(run away) The most common cause of problems in DC motors is ___________ related.
6.	(brush)

TYPES OF INDUCTION MOTORS

As you know from your study of generators, you use the magnetic induction principle along with the left-hand rule to explain generator action. A generator converts mechanical energy into electrical energy and a motor converts electrical energy into mechanical energy (motion). As you learned earlier in your studies, meter movements work on the motor principle. You also learned that motors use the right-hand rule to describe induction.

Induction motors are classified according to their internal construction. Internal construction types are the series wound, shunt wound, compound type, and universal type. You will now examine each of these types of motor construction.

Series Motor

In series motors, the field coils are in series with the armature. In other words, the same current that flows through the armature flows in the field windings. This is shown in Figure 7-4A on the next page.

A series motor must always use a resistive load. Without a resistive load, as the speed of the armature increases, the counter electromagnetic induction increases. The increasing counter emf causes a decrease in the armature's current. This decreasing current causes the field to start to collapse. As the field collapses, it provides an inductive kick to the armature current. As this cycle continues, current keeps increasing until the motor reaches a speed at which it self-destructs. This is referred to as motor run-away.

Another disadvantage of a series motor is its tendency to heat up. This is due to its high torque and resistive load requirement. When the motor overheats it wastes power.

Series motors are usually used to move heavy loads. They develop maximum torque (turning power) and are geared down as the speed starts to increase. You can install a resistor in series as shown in Figure 7-4B to control the speed of a series-type motor. The variable resistor provides a method to adjust the current. The current in turn has control of the magnetic field strength, which controls the induced voltage in the armature. Anytime you add a resistance in a series loop, current decreases in that loop.

You can use series-type motors with DC or AC inputs.

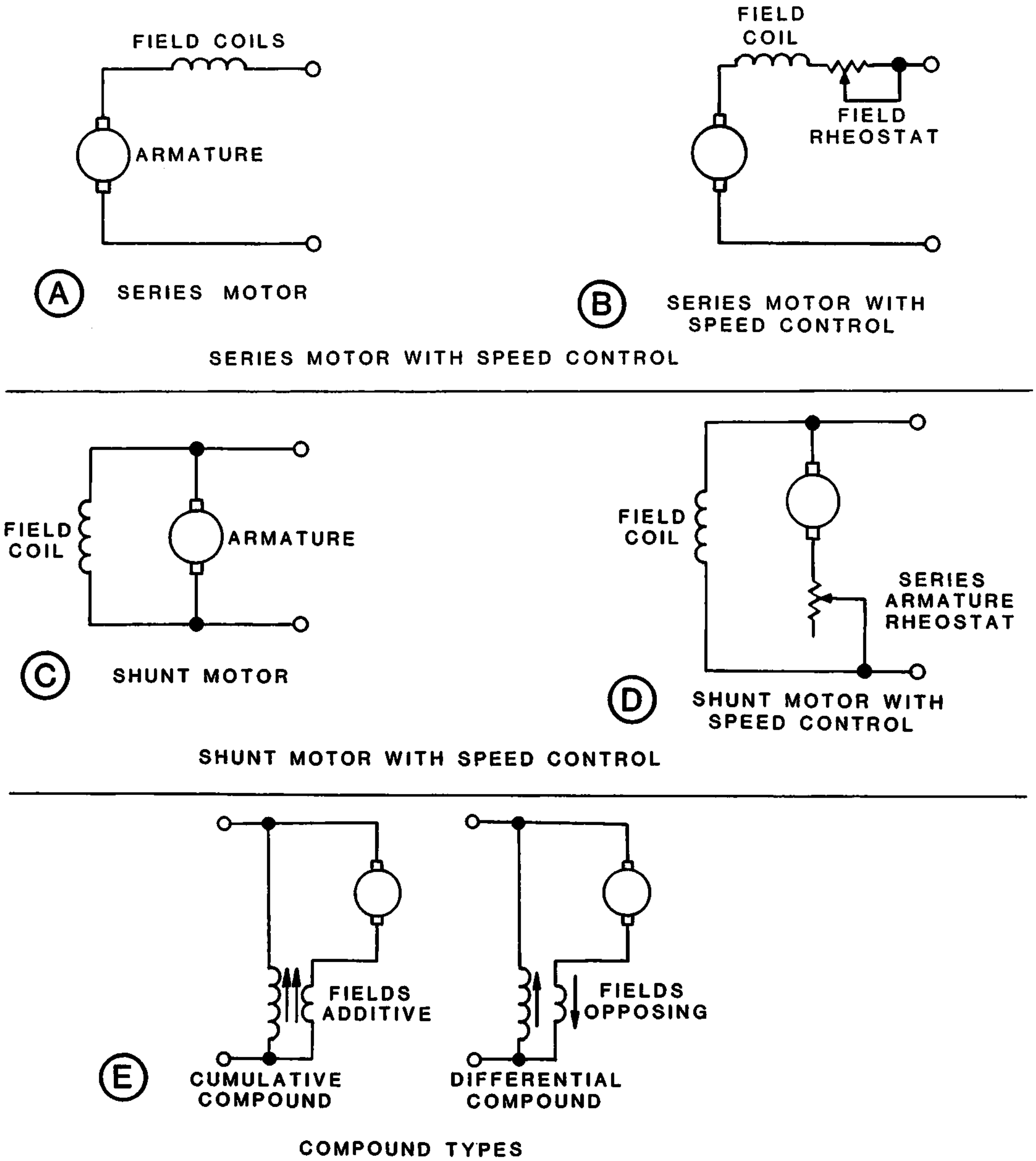


Figure 7-4
Induction-type motors.

Shunt Motor

A shunt motor is shown in Figure 7-4C. In this type motor, the field windings are connected in shunt (parallel) with the armature. The shunt motor is classified as a constant-speed motor. Soon after the motor starts, it reaches a speed at which the field and armature currents are almost equal. This speed is considered to be the motor's constant speed. The constant speed characteristic of a shunt motor is considered to be its primary advantage. Low torque is the main disadvantage of shunt-type motors.

You can install a resistor in series with either the field or the armature to change the constant speed of a shunt motor. In Figure 7-4D, the speed control resistor is in series with the armature. Note that the inductor (field winding) parallels both the resistor and the armature.

The resistor in series with the field winding reduces the current flowing in the field. When the field current decreases, it reduces the voltage that is induced into the armature. The induced voltage opposes the polarity of the voltage that caused it. This reduces the opposition to the motor's rotation and increases the motor's speed. Unfortunately, the resistor also reduces the motor's power efficiency rating. As is usually the case, in most electronic circuits, efficiency is sacrificed to achieve control.

Thus, when you install the resistor in series with the armature, you decrease the armature's current, which decreases the motor's speed of operation.

You do not normally use a shunt-type motor with AC.

Compound Motors

Compound motors use both series and shunt fields. This is shown in Figure 7-4E. The series winding provides a high starting torque, which overcomes initial friction. Once the motor approaches operating speed, the shunt winding takes control and the constant speed characteristic becomes the most important characteristic. A compound motor combines the advantage of both types (series and parallel) of motors, and at the same time compensates for their disadvantages. This results in a constant speed motor that is capable of developing high torque. It also eliminates the possibility of thermal runaway.

Compound motors come in two varieties. When the series and parallel windings are wound so that they aid each other, the motor is called a cumulative compound motor. When the series and parallel windings are wound so they oppose each other, the motor is called a *differential* compound motor.

You use a compound motor with DC input voltages.

Universal Motor

The universal motor is a series type motor that uses resistors in series with its brushes to limit high currents. The added resistance also reduces brush arcing. The universal motor is usually limited to low power applications (fractional horsepower ratings). Universal motors are used in small electric hand drills, small fans, and toys.

A DC motor can be used as a generator. The AC motor cannot be used as a generator.

Programmed Review

7.	The three types of construction used in induction motors are __________, __________, and __________.
8.	(series, shunt, compound) A motor that is used with both AC and DC voltages is called a/an __________ motor.
9.	(universal) Which type motor is **NOT** normally used with AC? __________.
10.	(shunt) A resistor connected in series with the stator winding causes the motor speed to __________ (increase/decrease).
11.	(increase) When a motor has both series and parallel-aiding fields, it is called a __________ __________ type.
12.	(cumulative compound) When the series and parallel fields oppose each other, the motor is a __________ __________ type.
13.	(differential compound) In a compound motor, which winding provides the high starting torque that is needed to overcome initial friction and inertia? __________ winding.
14.	(series) Maximum torque and friction occur when the motor is at __________.
15.	(rest)

AC MOTORS

As you learned earlier, you can use a series-type motor as an AC motor, but you must keep the induced current low.

Besides the universal motor, there are several types of AC motors that are commonly used. Most of the motors in your home fall into the following motor classifications: single-phase, two-phase, or three-phase. In addition, there is a classification called polyphase motors. In general the term polyphase means two or more phases.

In this course, the polyphase motor is a three-phase motor. Three-phase motors are very common in every home. Motors that require more than three phases are specific function motors like those that are used in heavy industry.

The following descriptions are limited to the types of motors that you are most likely to see. You will begin the description with the single-phase motor.

Single-phase Motors

The single-phase motor consists of a rotor and two stator windings as shown in Figure 7-5. The unequal magnetic fields around the stator windings force the rotor to turn. The stator fields are unequal because the two fields (start and run) are made of different diameter wires, and there is a different number of turns in the windings. This automatically causes a lead/lag difference between the stator's fields. The rotor starts to turn toward the stronger stator field. The AC input causes the stator's electromagnetic field to continually change. The rotor reacts to the induced change. However, the rotor can never overtake the stator fields. The effect can never overcome the cause in a mechanical system.

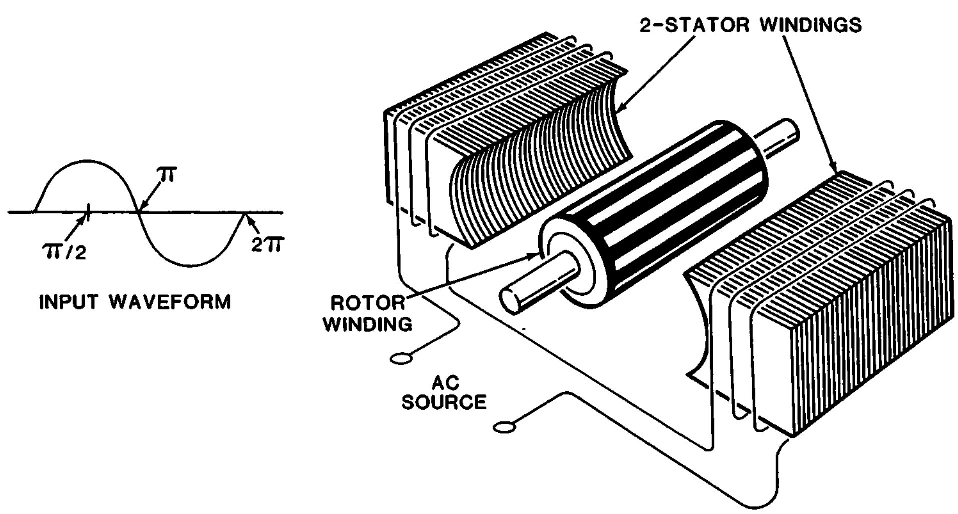


Figure 7-5
Single-phase motor.

You can start an induction motor by placing its starter field 90° from the run field. Since the winding has some resistive component, the phase angle is slightly less than 90°. This physical separation induces a current into the armature that overcomes friction and inertia. When friction and inertia are overcome, the motor starts to rotate. Once rotation has started, there is relative motion and magnetic fields are continually produced. The faster the motor turns, the stronger the attraction to turn. This is true until the motor reaches the speed of operation. Once it reaches the speed of operation, the armature and stator winding are separated by a predetermined amount.

The following description combines some of the knowledge that you earlier to explain angular motion, and some of the common terms that are used to describe generator and motor actions.

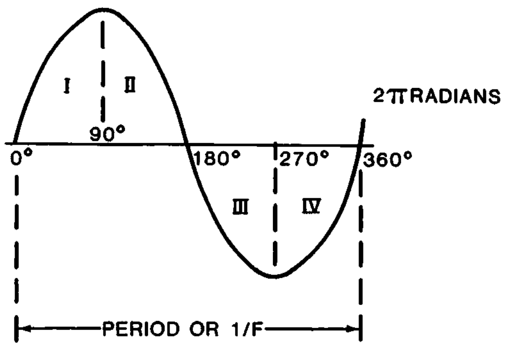
Note in Figure 7-5 that the input waveform is an AC sine wave that is marked as $\pi/2$, π, $\pi/4$, and 2π. As you know, the sine wave rotates for one complete cycle that is equal to 360°. You also measure the sine wave in radians per second, and a radian is approximately equal to 57.3°. The term radian represents angular displacement.

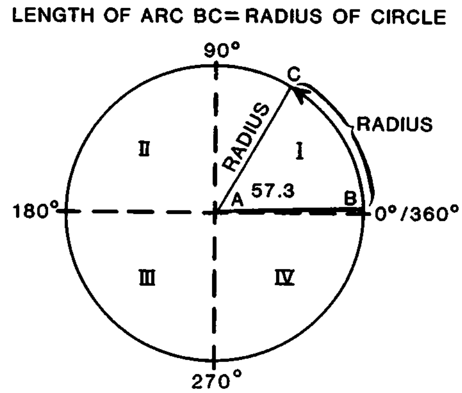
The sine wave is a vector that rotates counterclockwise for 360°. A radian is an angle that intercepts an arc (B to C) that is equal in length to the radius (C to A) of a circle as illustrated in Figure 7-6.

When an armature rotates one complete cycle, regardless of whether it is generating a sine wave (generators), or being driven by a sine wave (AC motor), the armature rotates through 360° or 2π radians. The circle is divided into 4 (IV) equal quadrants.

In Figure 7-6, the sign of the angle in each of the quadrants is listed (either positive or negative) for the sine, cosine, and tangent function of the angle.

Remember, motors use windings and windings are essentially inductive components. In inductive components, voltage leads current.





Signs of the Functions

Quadrant	sin θ	cos θ	tan θ
I	+	+	+
II	+	−	−
III	−	−	+
IV	−	+	−

$\pi \approx 3.14$

6.28 radians = 360°

2π radians = 360°

π radians = 180°

1 radians = 57.2958°

1 degree = 0.01745 radian

SIN OF 57.3° = .8415

COS OF 57.3° = .5402

TAN OF 57.3° = 1.5577

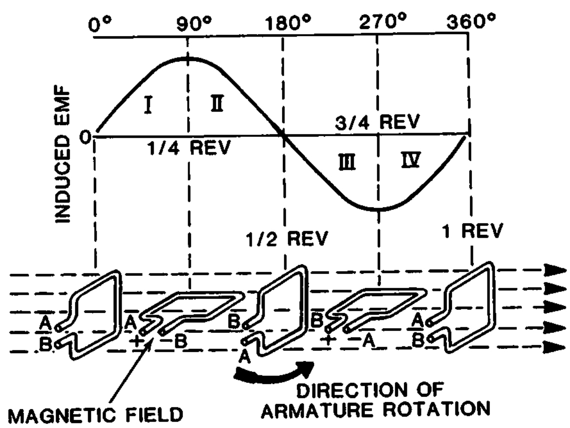


Figure 7-6
Angular rotation relationships.

When the single-phase motor comes up to speed, a centrifugal switch disconnects the starter (stator S_1) winding. Until you remove power from the circuit or an increased load slows the motor to the point where the centrifugal switch is reconnected, the motor uses the run (stator S_2) winding so it continues to turn. This is shown in Figure 7-7.

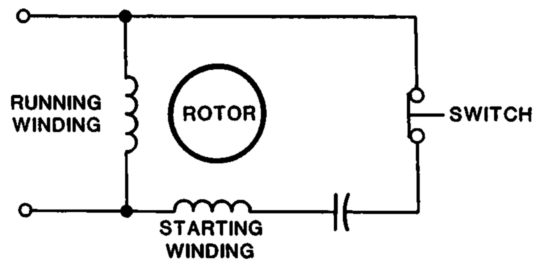


Figure 7-7
A single (split phase) motor with
a capacitor and centrifugal switch.

You can install a capacitor as shown in Figure 7-7. Here, the capacitor has been connected between the stator windings to increase the phase difference between stator windings. Increasing the phase difference causes the current to lead (ICE) the voltage and increases the starting torque of the motor.

Shaded motor poles also increase the starting torque of a motor. With a shaded pole, a portion of a pole face has a heavy copper wire wrapped around it. This causes a higher induced current in one side of the pole face. The shading acts as an aid in starting rotation.

Two-phase Motors

A two-phase motor is the simplest form of polyphase motors that is used in industry. The term polyphase describes any motor that has more than one input. (Two-phase motors are mainly used as servomotors. The servomotor is covered in more detail later in this unit). For now, a two-phase motor is a motor that has two inputs that are 180° out of phase. The two-phase motor must be driven from two separate inputs. To reverse the direction of rotation, simply reverse the inputs. A typical two phase motor is shown in Figure 7-8.

Polyphase Motors

Any motor with more than one input is considered a polyphase motor. Industry uses more three-phase motors than any other type. Applications that require power ratings above a fraction of a horsepower nearly always have three or more input windings.

In fact, the three-phase motor is so common that the terms polyphase and three-phase are used interchangeably. Polyphase motors use a squirrel cage rotor like the one shown in Figure 7-8.

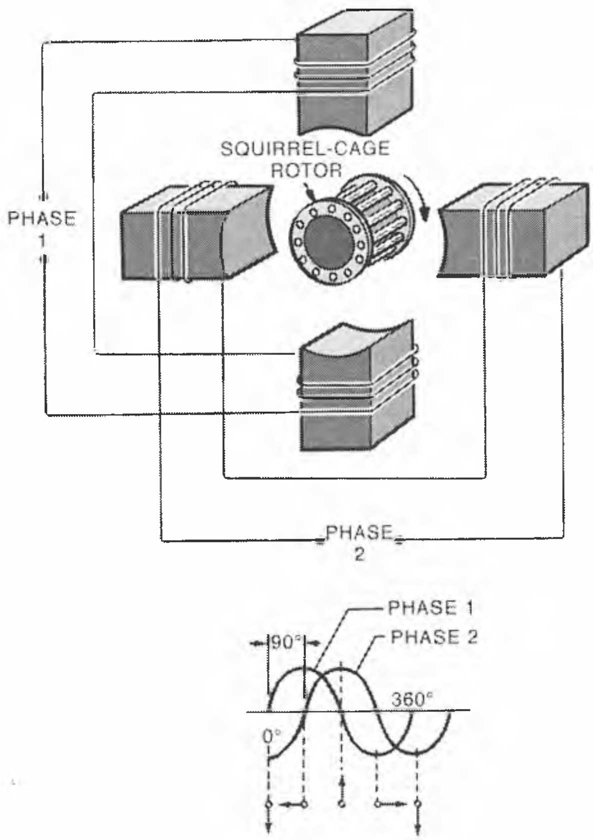


Figure 7-8
Two-phase motor.

As shown in Figure 7-9, a three-phase motor uses three inputs that are separated by 120°. To accomplish this, three stator windings that are electrically separated by 120 degrees are positioned around a squirrel cage rotor. To reverse the direction of rotation in a 3 phase motor, just reverse any 2 of the 3 inputs.

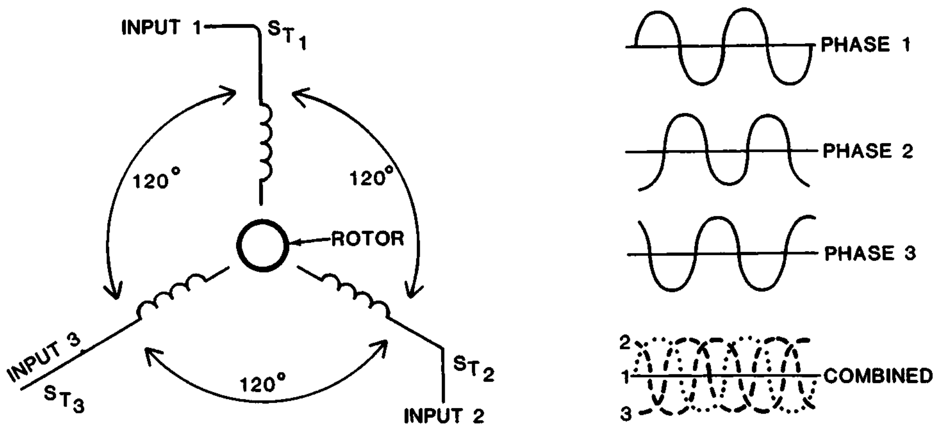


Figure 7-9
Polyphase motor contains a rotor and 3-stator winding that are separated by 120°.

Three-phase motors may use one of two wiring configurations. The stator windings may be wound in the delta or Y (star) configurations as shown in Figure 7-10. In the delta winding, an input is applied across a single winding. In this case, the voltage is lower and the current higher than is the case with the Y or star winding. In the Y or star wiring configuration, the input is applied across two windings and the developed voltage is higher, but the current is lower than in the

delta configuration. The number of turns in the winding or windings is directly proportional to the impedance (resistance). Remember, Ohm's Law states that ($E = IR$) current and resistance are inversely proportional, as long as you hold the voltage constant.

You should check three-phase motors periodically to ensure that they are operating at the proper speed and temperature. When one of the phases of an operating three-phase motor opens, the motor runs slower and heats up. You may not be able to detect this in some applications until the internally generated heat completely destroys the motor.

A simple three-phase motor has a pair of poles for each phase. Therefore, a two-pole, three-phase motor has 6 poles. The poles are separated by 60° (6 × 60° = 360°).

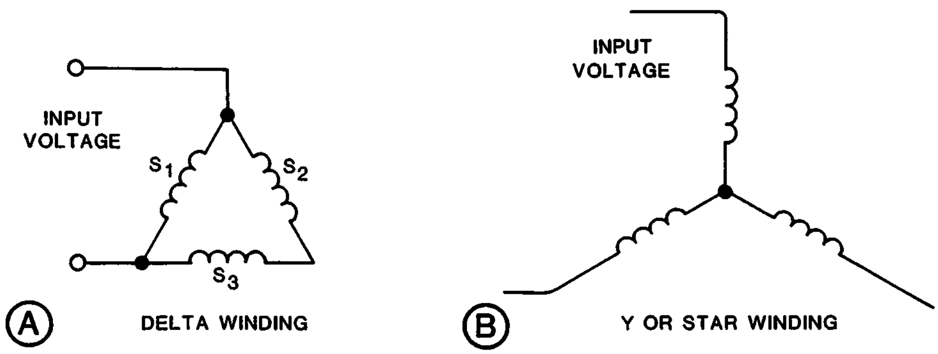


Figure 7-10
Motor winding configurations.
(a) delta-wound for high current.
(b) Y- or star-wound for high voltage.

Programmed Review

16.	The AC motor ____________ be used as a generator. can/cannot
17.	(cannot) The automatic speed control that is usually mounted directly on the motor is a ______________ switch.
18.	(centrifugal) The single phase motor contains a rotor and ____________ windings.
19.	(stator) To develop maximum torque, the stator winding should be ____________ from the rotor.
20.	(90°) 2π radians equals ______________________________________ .
21.	(360° or one revolution of a motor) A sine wave is a vector that rotates ______________________ . clockwise/counterclockwise
22.	(counterclockwise) The polarity of the cosine function in the third quadrant is _______________ . positive/negative
23.	(negative) A starting capacitor is connected in series with the starter winding to _______________ phase difference. increase/decrease
24.	(increase) The stator windings in a three-phase motor are electrically separated by _______________ degrees.
25.	(120) A polyphase motor is defined as a motor that has 2 or _______________ phases.

26.	(more) Single-phase motors usually have power rating that are in ___________ ___________ ___________.
27.	(fractional horse power) If one phase of a three-phase motor opens while it is in operation, the motor will ___________ ___________ and ___________ if the load is heavy enough.
28.	(slow down, overheat) When you convert a polyphase motor from Y wound to delta wound, this result is lower ___________ and higher ___________.
29.	(voltage, current)

MOTOR SPEEDS

Speed is motion or distance for a specific period of time. In a car, it is miles-per-hour or kilometers-per-hour. In motors, it is RPM (revolutions-per-minute) or RPS (revolutions-per-second).

Common terms associated with motor speeds are RPM (revolutions-per-minute), synchronous, and asynchronous. Synchronous and asynchronous are terms which compare the rotor's speed to the stator's speed.

RPM

You can use the following formula to calculate the term RPM for induction motors:

$$\text{RPM} = \frac{\text{VF}}{\text{P}}$$

Where:

RPM is revolutions-per-minute.

VF is the applied voltage and its frequency.

P is the number of poles that are produced in the stator's field.

For example: A 3-phase, 4-pole induction motor has an input voltage of 120 volts at 60 hertz. The motor's RPM is:

$$\text{RPM} = \frac{120 \times 60}{4}$$

$$\text{RPM} = \frac{7200}{4}$$

$$\text{RPM} = 1800$$

As you can see by the formula, either increasing the input voltage or increasing the frequency of the input, causes the motor to turn at a higher speed.

The 120 volts that is applied in this example is high for most electronic circuits. However, there are many motors in homes that operate with 120 volts.

If you increase the number of poles in a motor, the motor will turn at a slower speed, but with higher torque.

The counter emf in a motor is directly proportional to its speed and the strength of the magnetic field.

$$\text{counter emf} = \text{speed} \times \text{field strength}$$

You can rearrange the equation to get:

$$\text{speed} = \frac{\text{counter emf}}{\text{field strength}}$$

Therefore, speed is inversely proportional to field strength.

Motor Regulation

Most motors have a calculated regulation factor. In the case of a series motor, it must be regulated so that if the load opens, the motor doesn't continue to increase speed to the point where it self-destructs. You can connect a physical resistor in series with the stator winding to regulate the motor.

A motor requires more current to start rotating than it does to continue rotating. This makes sense because once friction is overcome, the start winding can be disconnected. This is usually accomplished with a centrifugal throw-out switch. The switch opens the starter winding when the motor reaches its run speed. The input voltage and the run winding then control the motor's speed.

Synchronous Speed

When a motor's rotor rotates at the same speed as the stator winding, the motor is called a *synchronous* motor. If this condition ever exists, there would be no relative motion between the stator and rotor fields. Without relative motion, there wouldn't be any drive current induced into the rotor.

Synchronous speed is an ideal term. In actual practice, when the rotor turns at almost the same speed as the stator, it is operating at its synchronous speed. Actually it oscillates in speed very close to the stator's speed.

A synchronous speed motor turns very fast, but has a very low torque capability. This makes the synchronous motor suitable for turning light loads at high speeds.

Asynchronous Speed

Asynchronous motors have a definite lag behind the stator windings. This lag is called *slippage*, and it is this slippage that determines the angle at which the stator field cuts the rotor's conductor material. The closer to 90° separation, between the stator windings and the rotor, the greater the number of lines cut. The higher the number of lines cut, the stronger the induced current. Maximum torque is developed at 90° of separation.

Percent of Regulation

Motor regulation is expressed as a percentage of the unloaded speed of operation. The amount (percentage) of regulation depends upon the actual load that the motor is turning. Thus, the more torque that must be generated to turn a load, the slower the motor turns.

The equation for a motor's percent of regulation is:

$$\frac{\text{no load speed} - \text{full load speed}}{\text{full load speed}} \times 100$$

For example, a motor has a no load speed of 1000 RPMs, but when it is fully loaded it has a speed of 800 RPMs. The percent of regulation for this example is:

$$\begin{aligned}\text{\% of regulation} &= \frac{1000 - 800}{800} \times 100 \\ &= \frac{200}{800} \times 100 \\ &= .25 \times 100 \\ &= 25\end{aligned}$$

The percent of regulation is 25 percent. This should not be confused with a motor's speed control. Speed control is a term which means external circuitry that is used to control the speed of a motor. You could consider the series resistor which is used to control a series DC motor and a centrifugal switch as external components to the basic motor.

Later in your studies of Semiconductor Devices and Electronic Circuits, you will study special devices and complete circuits that are used to control motor speed and motor direction of rotation.

Programmed Review

30.	When you compare synchronous and asynchronous motors, which type operates at the higher speed? ______________ .
31.	(synchronous) The amount of lag between a rotor and the stator field is defined as ____________ .
32.	(slippage) A simple three-phase motor has __________ poles.
33.	(6) Shading the motor's poles ______________ the motors starting torque? increases/decreases
34.	(increases) When increase the number of poles in a motor, the motor's speed ______________ . increases/decreases
35.	(decreases) When you increase the operating frequency of the applied voltage, the motor's speed ______________ . increases/decreases
36.	(increases) When you increase the magnetic field strength, the motors speed _______________ . increases/decreases
37.	(decreases) True synchronous speed occurs when the __________ and __________ fields move at the same speed..
38.	(rotor, stator) Torque and motor speed are _____________ proportional. directly/inversely
39.	(inversely) The voltage that is necessary to overcome the effects of friction and inertia is called _____________ voltage.

40.	(offset) The formula for % of regulation is: ______________________________.
41.	$\% \text{ REG} = \dfrac{\text{NO LOAD SPEED} - \text{FULL LOAD SPEED}}{\text{FULL LOAD SPEED}}$

MOTOR CONTROL CIRCUITS

It is possible to use a switch to turn a DC motor on and off. However, there are times when you will want to vary the speed or direction of the motor rotation. To do this, you can use resistors or variable resistors to control the motor.

DC Control Circuits

Figure 7-11 shows the simplest DC motor control circuit. In the figure, the DC motor is shown as a circle with an M inside the symbol. This is the schematic symbol for a DC motor. Switch S_1, controls the power to the circuit. Ultimately, this switch determines whether or not the motor is running. Resistor R_1 is a series-limiting resistor. This resistor prevents excessive current from flowing through the circuit when the motor operates without a load. It is good practice to have a current-limiting resistor in the circuit anytime a motor is connected in series with a DC power source. The actual control in the circuit is variable resistor R_2.

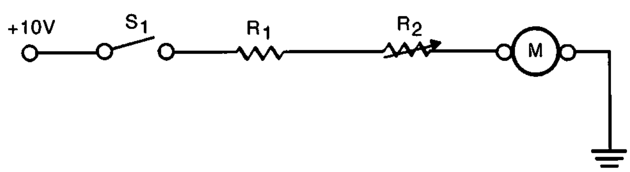


Figure 7-11
Elementary DC motor control.

Variable resistor R_2 actually controls circuit current. When you adjust R_2 to its maximum resistance, it severely restricts the voltage drop across the motor, and therefore the current through the motor. This results in the motor turning at a slower speed. As you adjust the resistor for less resistance, the motor speeds up. In this way, you can use R_2 to control the speed of a DC motor.

You might assume that even when R_2 is set to its maximum value, the motor would begin to rotate the instant you close switch S_1. This, however, is not true because one of the fundamental laws of physics states that **"Bodies in motion tend to remain in motion, and bodies at rest tend to remain at rest"**. In order to start rotating and come up to operating speed, the motor must overcome two quantities: inertia and friction.

Friction is the resistance to relative motion between two objects in contact. In other words, any time two objects come into contact they tend to hold each other in place. In a DC motor, there are many points of contact. Most of the friction is the contact between the brushes and the commutator.

Inertia is the property of an object by which it remains in motion or at rest, unless it is acted upon by some external force. Inertia results from the mass of an object. The greater the mass, the greater the force necessary to overcome the inertia. Anyone who has tried to push a stalled automobile can readily understand this concept. The weight of the object (automobile or armature) is a direct effect of the gravitational force which acts upon it. Since weight is proportional to mass, the analogy between weight and mass is valid. It takes a certain amount of energy to overcome the properties of friction and inertia in a DC motor. For this reason, you must apply a given amount of voltage to the motor before it develops enough torque, or twisting force, to begin turning. This voltage is called the *offset voltage*. In a well designed DC motor control circuit, you select components to compensate for torque and inertia to ensure that the voltage applied to the motor always meets or exceeds the value of the offset voltage. This, along with the starter winding that is electrically positioned at 90° in relationship to the armature, will start motor rotation.

Incidentally, once you overcome inertia and friction, and the motor is running, you can decrease the voltage applied to the motor and still maintain its operating speed. This principle also applies to changing loads. When you increase the load, the current must also increase to maintain the same speed. To accomplish this, you can either increase the applied voltage or decrease the resistance. When you decrease the load, you must decrease the applied voltage or increase the resistance to maintain the same motor speed. More armature current is always required to move a heavier load.

Sometimes, you might need to change a motor's direction of rotation. Figure 7-12 shows a motor control circuit which consists of a potentiometer, switch, limiting resistor, and DC motor. In this figure, the wiper (center tap) on the potentiometer is centered. That is, the resistance between points A and B equals the resistance between points B and C. At point B, the voltage is 10 volts positive with respect to one power supply and 10 volts negative with respect to the other. In this configuration, current flows between the +10 V supply and the –10 V supply and no current flows through the motor. This is the motor's null (no difference of potential) position and the motor is at rest (stationary).

As you move the potentiometer from its centered position, current begins to flow through the motor. This is shown in Figure 7-12B. Note here that there is much less resistance between the –10 V supply and ground than there is between the +10 V supply and ground. Therefore, the current flows from left to right in the illustration which causes the motor to rotate in one direction.

When you adjust the potentiometer in the other direction, current begins to flow from right to left as shown in Figure 7-12C. In this instance, the motor direction changes along with the direction of current flow through the motor. The motor in examples 7-12B and 7-12C turns in opposite directions.

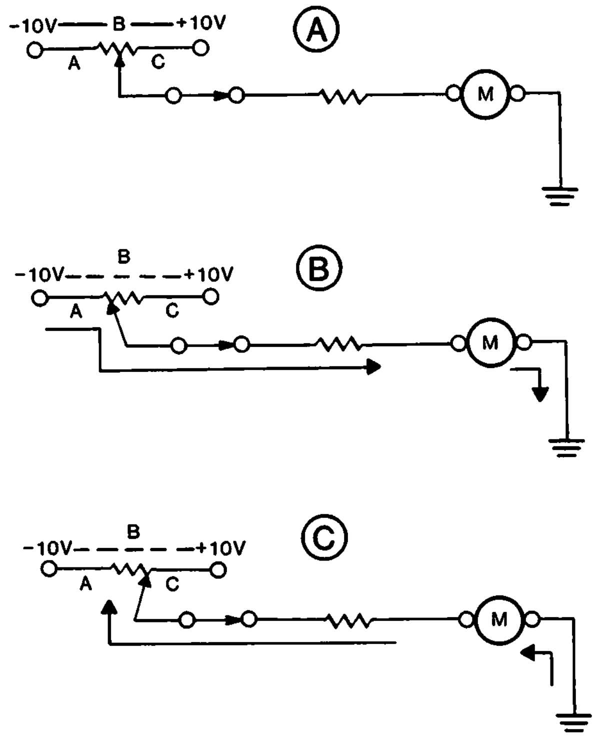


Figure 7-12
DC motor direction and speed control.

Besides changing direction, you can use the potentiometer to vary the speed of the motor. However, the same problems of inertia and friction occur with this control as did with the variable resistor and single voltage source used in Figure 7-11. The advantage of using both a positive and a negative source is that you can null and reverse the motor without changing the circuit wiring.

The squeeze trigger device is another type of control device which is used to regulate the speed of a drill, or to regulate the speed of toy cars on a slot car racing track. Soldering guns also use these devices to control the amount of heat. The squeeze trigger device is simply a series variable resistance that you adjust by finger pressure.

Remote Controls

The term remote control means control at a distance. For example, the garage door opener that you use while still seated in your car is a remote control device.

A relay is the most common remote control device. A garage door opener uses a relay along with an RF transmitter and RF receiver. The transmitter that you carry in your car sends out a radio frequency signal that is picked up by a receiver inside the garage. The receiver triggers a relay that activates the motor which lifts or lowers the garage door. There is usually a switch located in the house or garage that is directly wired to the relay. The switch is an alternate remote control device to open or close the garage door.

The lock-in or lock-out box, which is usually located near industrial machines, is another example of control at a distance. Most assembly lines have this safety feature. This ensures that you are ready for the motors to be started or stopped. Most dangerous machines require you to close two switches before operation can begin. You can turn these same machines off by either of the switches.

A microswitch is another common safety device that provides control at a distance. You can configure (wire) microswitches to either turn on or turn off, and they are often used as pressure sensors or limit switches. A microswitch is the type of control that senses when the garage door is fully opened and closed. Microswitches are commonly called limit switches. When the door reaches its limit (fully open or fully closed) the microswitch disconnects the relay from the drive motor.

Most heavy duty motors are equipped with a thermo-switch that is set to the maximum safe operating temperature of the motor. When the temperature of the motor exceeds the switch's setting, the switch opens and shuts the motor off. Many of these thermo-switches reactivate once they cool below a specific temperature. You must manually reset others, like a circuit breaker. These types of control devices provide thermal protection or heat control. These heat-sensing switches use the thermocouple principle to operate.

These motor control circuits are very simple and are meant only as an introduction to motor controls.

MOTOR CONTROL SYSTEMS

Some controls are built into the motor. Other motor controls are components that are mounted directly on the motor. For example, the size and direction in which the fields are wound is a built-in control. A resistor in series with the winding, the centrifugal switch, and the thermal cut-off switch are examples of add-on features.

The control circuit is often a complete system. For example, the heating system in a house is a complete control system. The furnace (source) supplies the heat. The convection air currents form the loop (conductor path). The thermostat provides a reference and error detection. The thermostat also sends out a correction signal. A system that is controlled by a feedback loop (the air currents) is considered to be a closed-loop system. When a system must be continually adjusted (such as increasing and decreasing a potentiometer) to maintain a constant speed, the system is considered to be an open-loop system.

A switch control system is sometimes called a go/no-go or bang-bang system. For example, there are no decisions or comparisons to be made in a go/no-go system. You can use a light switch in your home to turn a light off or on. If the light is already on, the switch can only turn the light off.

Remote Control System

The automatic garage door opener is a remote control system that contains a motor. In this case, the system is made up of a transmitter, a receiver, and motor. The transmitter is carried in the car (a remote location) and the receiver is located in the garage. The transmitter sends out RF pulses, the receiver intercepts the pulses, and starts the motor. Limit switches or pressure switches turn the motor off when the work (opening or closing the door) is accomplished. The garage door opener is an example of a radio-controlled system. The RF (radio frequency) pulses are made up of frequencies in the radio-frequency band.

There are other common motor control systems in use in industry and other applications. The two most common are called synchro systems and servo systems.

Synchro Systems

The basic synchro system is a device for angular positioning of a shaft to indicate position, or to turn a load. A synchro system does not provide amplification and is considered to be a 1:1 device. In other words, the mechanical power that is applied is equal to the mechanical power out. This is very similar to transformer operation. In fact, it is some times referred to as a variable transformer application.

The synchro system is usually made up of 3 elements. The 3 elements are a synchro transmitter (TX), synchro differential transmitter (CDX), and a synchro receiver (RX). A basic synchro system block diagram is shown in Figure 7-13.

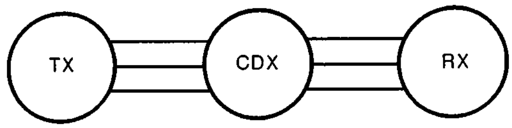


Figure 7-13
Block diagram of a synchro system.

BALANCED SYSTEMS

The relationship between the synchro's rotor and stator windings is usually a ratio of 2.2:1. For example, when 115 volts AC at 60 hertz is applied to the rotor winding, it induces 52 volts into the stator winding with which it is aligned. Figure 7-14 illustrates the voltages that are developed across each winding when the rotor is aligned with stator winding S_2. Note that the voltage that is induced into S_2 is 52 volts AC. When R_1 is aligned with S_2, R_2 is aligned with the 180° position.

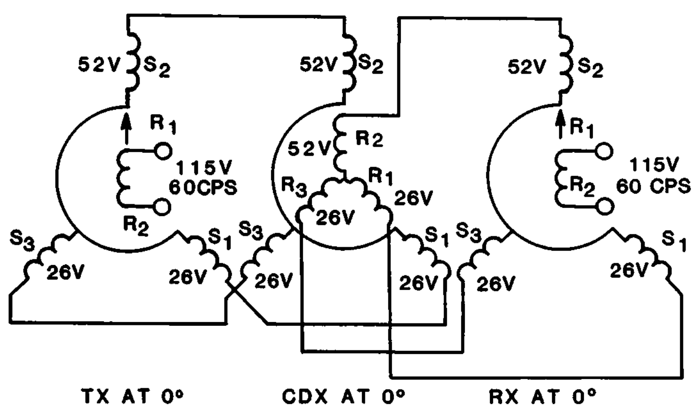


Figure 7-14
Balanced synchro system.

The stator windings are spaced 120° apart. When S_2 is at 0°, S_3 will be at 120°, and S_1 will be at 240°. Since the maximum induced voltage into a winding is 52 volts and the rotor is aligned halfway between S_3 and S_1, the voltage induced into S_3 and S_1 is 26 volts.

The voltage that is induced from the reference stator winding to the end of either of the other stator windings is always 78 volts. In most synchro systems, stator winding S_2 is defined as the reference stator winding. Note that in Figure 7-14 the rotors in the synchro transmitter and the synchro receiver are aligned. Note also that the voltages which are developed across the windings of both the transmitter and receiver are equal.

DIRECT-COUPLED SYSTEMS

Note that in Figure 7-15 the synchro transmitter and receiver appear to be electrically the same. However, they do differ because the transmitter's rotor is not free to turn and the receiver's rotor is free to turn. The transmitter's rotor is normally coupled to an input shaft. The input shaft loads the rotor so that it does not move by electromagnetic induction. When the input shaft is mechanically rotated, the transmitter's rotor winding rotates and develops a voltage across its three stator windings. The amount of voltage that is developed is determined by the angular displacement of the input shaft. The voltage that is developed across the stator's windings determines the amount (degrees of rotation) that the rotor moved.

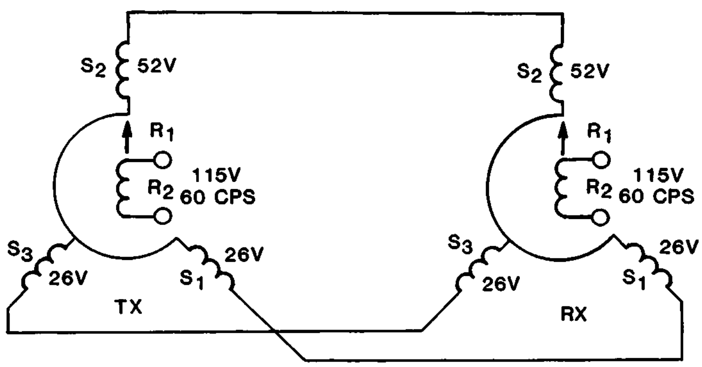


Figure 7-15
Synchro transmitter and receiver.

The stator windings of the synchro transmitter are connected to the stator windings of the synchro receiver. The synchro receiver's rotor is free to turn. The rotor of the synchro receiver is usually connected to a dial pointer (very light load). The receiver rotor's position is controlled by the voltages that are developed in the receiver's stator windings. The receiver's rotor repositions the dial pointer to indicate the new angular position of the input shaft.

UNBALANCED SYSTEMS

For example, when the input shaft is attached to the rotor of the synchro transmitter and it is rotated to the right 30°, the transmitter's rotor develops a voltage across its stator windings. This developed voltage is coupled to the receiver's stator windings. The stator windings in the synchro receiver induce a current into the receiver's rotor that causes it to rotate 30° to the right. The amount of displacement of the transmitter's rotor is indicated by a pointer that is attached to the receiver's rotor.

Electrically, the synchro transmitter is equivalent to a transformer. In this analogy, the rotor is the primary winding and the stator windings are the secondary. In the synchro receiver, the stator winding acts as the primary and the rotor winding acts as the secondary.

A synchro transmitter and receiver combination is used in remote indicator applications. For example, a compass indicator in the cockpit of an aircraft uses this system. The synchro receiver is built into the indicator located in the cockpit. The synchro transmitter is part of the compass located in the aircraft electronic compartment.

DIFFERENTIAL SYNCHRO SYSTEMS

Another type of synchro system that uses 3 elements is shown in Figure 7-16. In this configuration, the synchro transmitter and receiver are separated, and a synchro control transmitter is added between the transmitter and receiver. Note that the differential transmitter has 3 rotor windings and 3 stator windings. The windings are again separated by 120° and the turns ratio between the rotor windings and stator windings are 1:1.

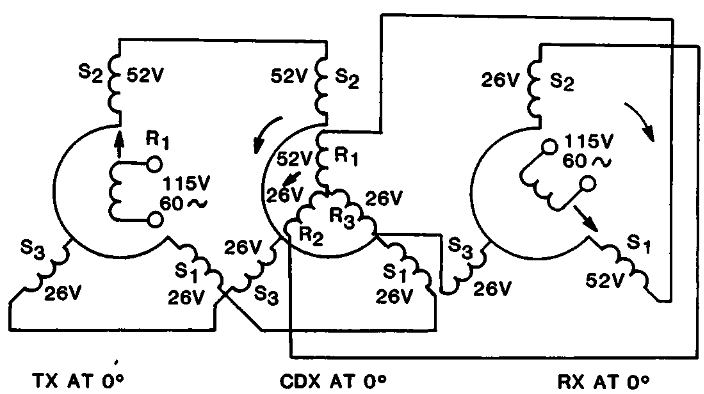


Figure 7-16
Synchro differential system.

THE DIFFERENTIAL TRANSMITTER (CDX)

A differential transmitter (CDX) is an error detection device. It senses the difference between the synchro transmitter (input device) and the synchro receiver (output device). Note that the differential stator windings are connected to the stator windings of the synchro transmitter. Its rotor windings are connected to the receiver's stator windings.

The rotor of the differential transmitter is not free to turn. It can be mechanically repositioned to program a difference reading. Note that in Figure 7-16, when the differential transmitter is turned to the 120° position, and the transmitter is set to the zero position, the receiver rotates to the 240° position.

In other words, the receiver rotates 120° in the opposite direction. When it is used in this configuration, the receiver setting equals the transmitter setting minus the differential transmitter setting.

$$TX - CDX = RX$$

$$0 \text{ or } 360 - 120 = 240$$

When the differential transmitter is connected as shown in Figure 7-17, the receiver indicates the sum of the transmitter and differential transmitter settings. Compare the synchro configurations shown in Figure 7-16 and 7-17. You should have noted that you reverse windings to accomplish the change from a difference detector to a summing detector. You must reverse windings R_1 and R_3, and S_1 and S_3 in the differential transmitter for the summing operation.

$$TX + CDX = RX$$

$$0 \text{ or } 360 + 120 = 120$$

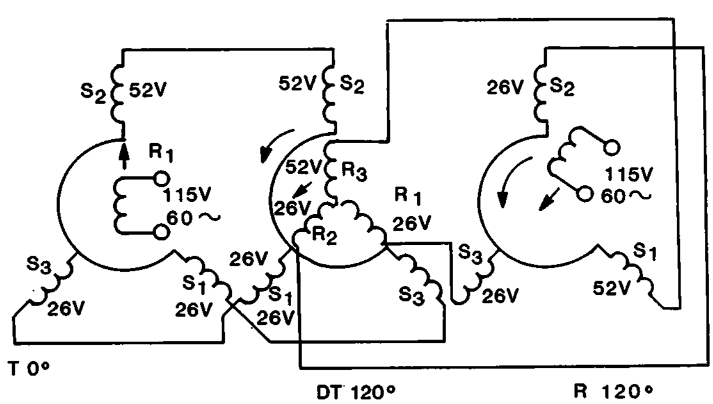


Figure 7-17
Synchro tracking system.

Figure 7-18 is a simplified wiring diagram of a synchro adder. Compare this wiring diagram to the circuit shown in Figure 7-17. Both circuits perform the same function and are therefore considered to be equivalent circuits.

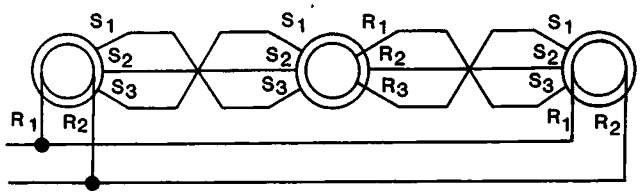


Figure 7-18
Wiring diagram for tracking systems.

THE DIFFERENTIAL RECEIVER (CDR)

There is also a differential receiver (CDR) that is very similar to the differential transmitter. The primary difference between the differential transmitter and receiver is in the rotors. The rotor in the differential transmitter is not free to turn. It must be mechanically repositioned. In the differential receiver the rotor is free to turn.

When you use a differential receiver between a synchro transmitter and synchro receiver as shown in Figure 7-19, and reposition the transmitter's rotor, it sets up a field in the stator windings of the CDR. This field induces a current through the CDR's rotor. The rotor of the CDR develops a field in the stator windings of the synchro receiver. This field causes the synchro receiver's rotor to turn. The synchro receiver's moving rotor induces a current back into the receiver's stator windings. The synchro receiver continues to rotate until the field across the receiver's stator windings cancels the field developed in the differential receiver's rotor windings. At this time, the synchro receiver indicates the angular difference between the synchro transmitter and the differential receiver.

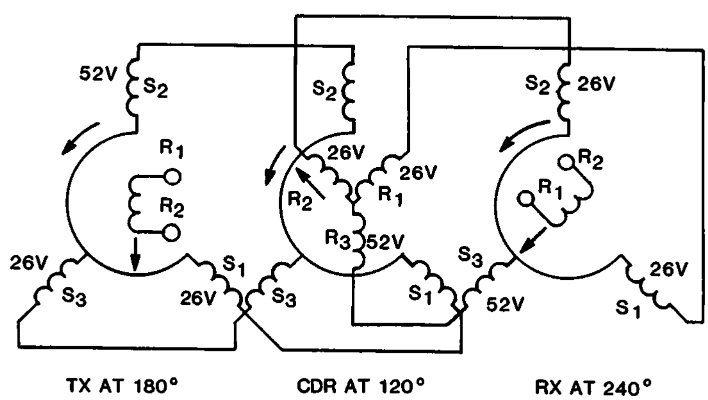


Figure 7-19
Synchro differential receiver between two synchro transmitters.

Servo Systems

A servomechanism is a mechanically-coupled device that is driven by a difference between its input and its output. The main parts of a servo system are a prime mover, a feedback loop, error detector, and an amplifying device. The prime mover is the servo motor, the feedback loop compares the output to a reference, or back to the input signal. The error detector is a component that determines the difference between the reference and the output. The amplifying device compensates for losses in the line. The losses could be from friction or line resistance. A typical servo system block diagram is shown in Figure 7-20.

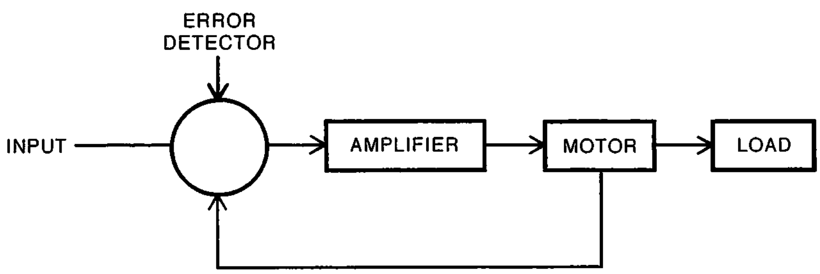


Figure 7-10
Block diagram of a typical servo.

AC SERVO SYSTEM

The conventional AC servo motor is a two-phase induction motor. One input is applied to the reference winding and the error input is applied to the control winding. When the input (reference) and the output are the same, there is no error voltage to detect. When there is a phase difference, the error voltage is applied to the control winding, and the servomotor turns until the input and output are in phase. As in other induction motors, maximum torque occurs when the input and output are out of phase by 90°.

DC SERVO SYSTEM

DC servomechanisms are high-torque devices and are used to move heavy loads. The motors are specially constructed to develop a linear proportional change in output current, for a change in input voltage. The DC servo motor moves much slower and smoother than the AC servo motor. Speed and direction of movement is easily controlled with DC servos.

AC servomechanisms are used in applications when fast response and low cost are the primary concerns. The constant speed aspect of AC motors makes control circuitry for the AC servomechanisms more complex than control circuits for DC servomechanisms.

Therefore, AC servomechanisms have faster response times and are less expensive than DC servomechanisms. DC servomechanisms are more accurate and require less control circuitry.

A HOME SERVO SYSTEM

The servo system shown in Figure 7-21 is the remote antenna adjustment system that is popular in home use. The rotor control usually sits near the television. When you change the television channel, sometimes you align the rotor control to a new direction. The electrical difference between the direction the antenna was pointing and the new direction is determined by the error detection component. Next, the error signal is coupled to the servo motor. The servo motor turns, sending a current to a drive motor. The antenna is physically attached to the drive motor, and it rotates as the motor drives. Once the motor has realigned to the reference, the error signal reduces to zero, and the motor stops turning.

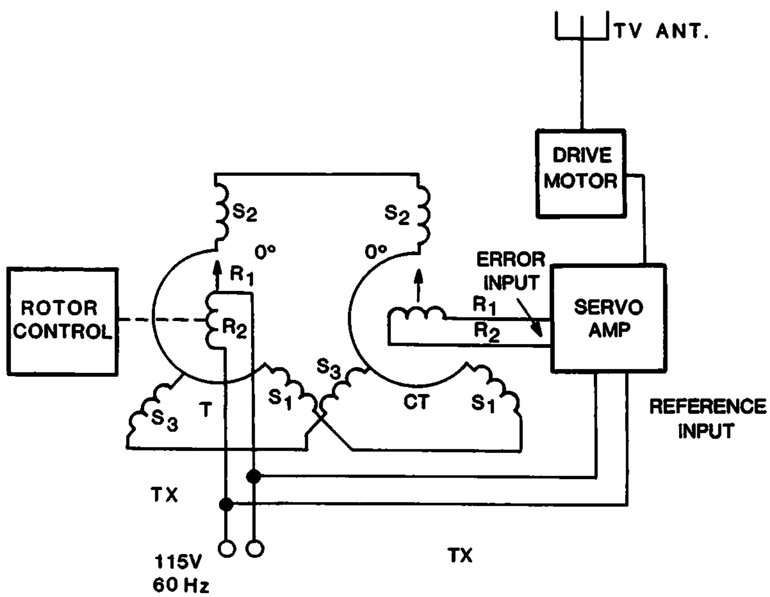


Figure 7-21
Home servo antenna control system.

FREQUENCY-CONTROLLED SERVO SYSTEMS

Model airplane flying is another example of a radio frequency remote control system. In this system, there are 2 sets of controls. One control is used to roll the plane and is called a *roll servo*. The roll servo controls the horizontal axis. The other control axis is nose up and nose down. It controls the plane's climb and dive, which is the vertical axis. This control is called a pitch servo.

Flying model airplanes require servo motors to be mounted in the airplane itself. Joy sticks are an electronic device that work on the same principle. A joy stick is part of many home video games. A joy stick controls the vertical and horizontal axis of a television set. To accomplish this, the joy stick varies the potential that is applied to the television's vertical and horizontal deflection plates. The television set operates much like the oscilloscope that was described earlier in this course.

Commercial and military airplanes have 3 servo systems to control their vertical and horizontal axis. They are roll, pitch, and yaw. The yaw servo keeps the nose of the plane from varying from side to side.

When the pilot selects autopilot, the servo systems are actually flying the airplane. That is, a reference is fed to the servos, and the servos receive information about altitude, drift, speed, direction of flight, and the plane's attitude in relationship to the horizon. When any of the references change, an error signal is automatically fed back to the servo. The servo then acts on the error signal and returns the airplane to the desired flight path.

Many servomechanisms have null and anti-hunt circuits built into the servomechanism's amplifier. These circuits dampen error signals to prevent over correction. Later, in your studies of Electronic Circuits you will study these nulling and anti-hunt circuits.

Comparing Synchro and Servo Systems

The basic servomechanism is a synchro system that is connected to an amplifier. Therefore, the primary difference between a synchro system and a servo system is gain. Synchros are considered to be unity-gain systems. Servo systems are high-gain systems. Both systems may use a feedback loop. The feedback loop is used to route the difference signal (error), back to the input for automatic correction. Automatic correction servos are examples of closed-loop operation. When the error is detected but not routed back to the input, it is an open-loop servo system.

The purpose of the amplifier in a servo system is to compensate for losses such as friction and inertia. The amplifier is also capable of supplying large currents to move heavy loads.

Programmed Review

42. When a motor is nulled, current ___________ flow.
does/does not

43. (does not) The turns ratio of the rotor winding to stator winding in a synchro transmitter is ___________ .

44. (2.2:1) The turns ratio of the rotor winding to the stator winding in a CDX is ___________ .

45. (1:1) The transmitter in the synchro system ___________ free to turn.
is/is not

46. (is not) The receiver in a synchro system is usually used to drive a/an ___________ ___________ .

47. (remote indicator) The synchro system usually doesn't contain an ___________ ___________ .

48. (amplifier block) The synchro transmitter's stator winding are connected to the ___________ windings.

49. (receiver or control differential stator) The differential transmitter has three stator windings and ___________ rotor windings.

50. (three) To convert a differential synchro system from a difference detector to a summation system, you should reverse the ___________ ___________ .

51. (S_1 and S_3 and R_1 and R_3 windings of the differential transmitter) The primary difference between a synchro and a servo system is ___________ .

52.	(gain or amplification) Electrically, a synchro transmitter is equivalent to a __________ __________ .
53.	(synchro receiver) The stator windings in a servo system are displaced from each other by __________ degrees.
54.	(120) The stator winding that is used as the standard in synchro transmitters and receivers is the __________ winding.
55.	(S_2 winding)

EXPERIMENT 11

Identifying Motor Symbols

OBJECTIVES: *To identify schematic drawings which represent various motors.*

To match motor applications to the symbol that represents the motor that is most used for that particular application.

To identify, by symbol, which motors are used with AC and DC supplies.

Introduction

This experiment provides you with some practice in identifying the motor symbols that are used in schematic drawings. It also serves to review the various motors that were described in this unit.

Procedure

1. In the spaces provided, select the symbol or symbols that represent the following types of motors. The motor symbols are located on the last page of this experiment.

   Series wound ________.

   Shunt wound ________.

   Compound wound ________.

   Three-phase ________.

   Two-phase ________.

   Single-phase ________.

   Induction type ________.

   Synchro ________.

   Universal type ________.

2. Which symbol or symbols represent a motor that could have series aiding or series opposing field windings? ______________.

3. Which symbol or symbols represent motors whose rotor winding have a 2.2 :1 ratio to their stator windings? ______________.

4. Which symbol or symbols represents a control differential transmitter? ______________.

5. Which symbol or symbols have their stator or field winding separated electrically by 120°? ______________.

6. Which symbol or symbols represent either a receiver or transmitter motor? ______________.

7. Which symbol or symbols have their rotor windings separated electrically by 120°? ______________.

8. Which symbol or symbols represent the motor that is most used to develop power ratings of more than 746 watts? ___________.

9. Which symbol represents the least expensive motor? ___________.

10. Which symbol or symbols are not used for AC applications? ______________.

Discussion

The motors in this experiment are all induction-type motors. There are generally divided into three categories. The categories are required voltage supply, type construction, and application.

Summary

The series-wound motor (I) is the most-commonly-used motor for small loads. It can be used in both AC and DC applications. When insert a small resistance in series with its brushes, it is called a universal motor (either AC or DC). Series motors also require some type of resistive load to prevent thermal runaway. The series motor uses a split field for its starting and running fields.

Shunt (A) and compound motors (H and J) are never used for AC applications. Shunt motors develop lower torque than series motors, but they have a higher starting speed. The shunt motor is considered to be a constant-speed motor.

Compound motors can have series-aiding (cumulative) or opposing (differential) fields. Compound motors usually have a starter field, which is disconnected (opened) by a centrifugal switch, when it approaches its running speed.

Single-phase motors are usually used for loads that require less than 1 horsepower.

Two-phase motors are normally used in synchro/servo systems. These systems are used to detect an error, or in automatic error correction systems.

Three-phase motors (K) have their stator windings electrically separated by 120°. They normally have a squirrel cage rotor, and are used for load requirements in excess of 746 watts.

Synchro motors (E) have three rotor and three stator windings which are electrically separated by 120°. The turns ratio from their rotor to stator winding is 1:1.

Servo motors (D) have 3 stator windings that are separated electrically by 120°. Stator S_2 is the reference winding in a servo motor. The turns ratio, from the rotor winding to the stator winding, is 2.2:1. When it is used in a circuit with amplification, the circuit is called a servomechanism. The servomechanism sometimes uses a synchro transmitter as its error detection component.

Almost all electrical motors are driven according to the electromagnetic induction principle. Therefore, most motors are induction motors.

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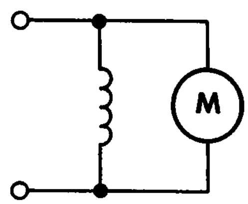

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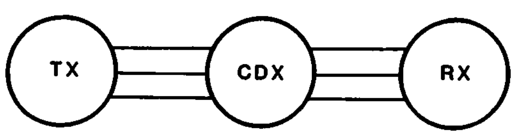

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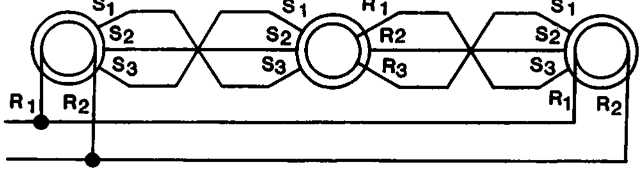

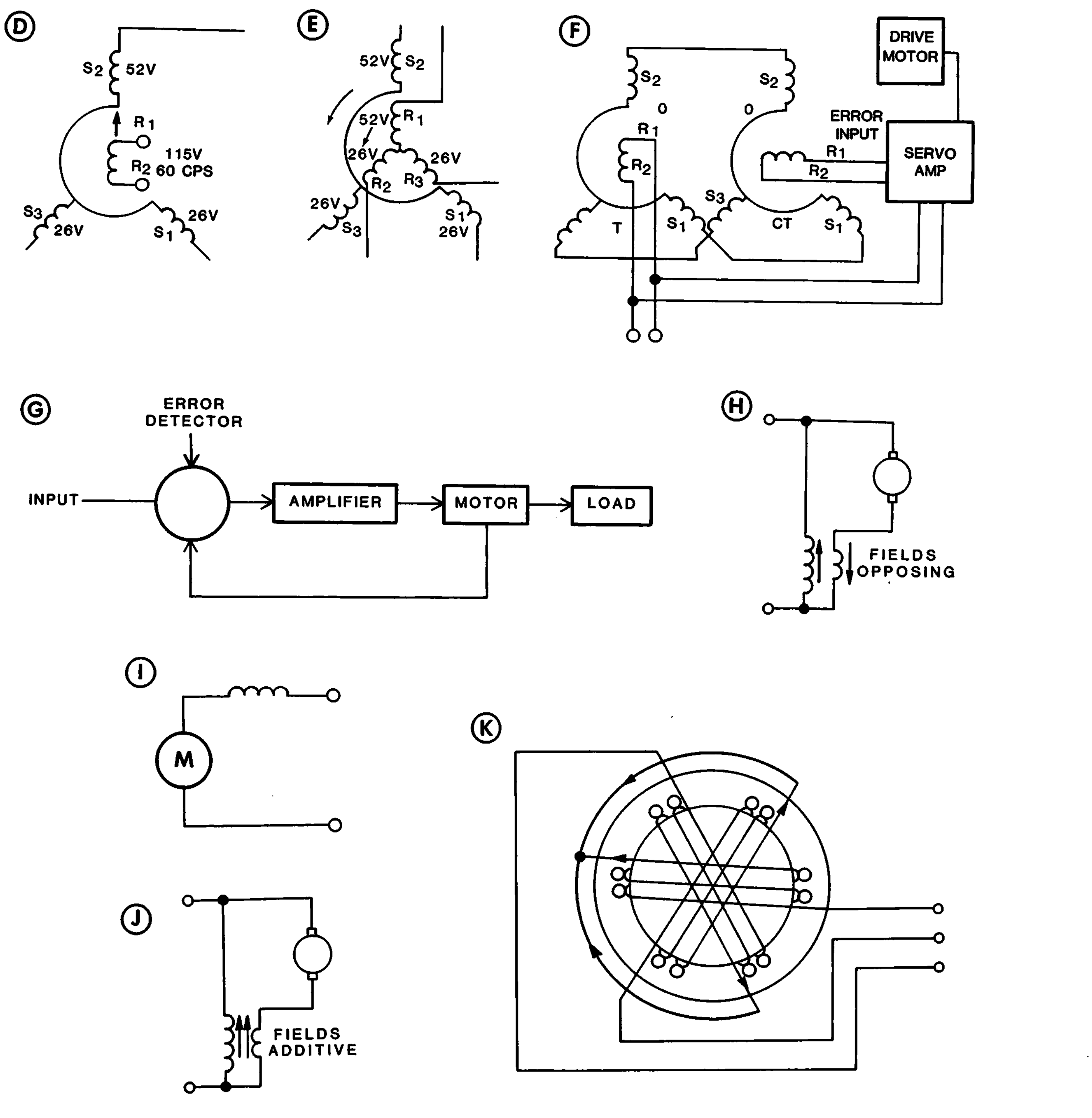
D
S2 52V
R1
115V
R2 60 CPS
S3 26V
26V S1
E
52V S2
52V R1
26V
26V
R2 R3
26V S3
S1 26V
F
S2
S2
0
0
R1
R2
T
S1
S3
CT
S1
DRIVE MOTOR
ERROR INPUT
R1
R2
SERVO AMP
G
ERROR DETECTOR
INPUT
AMPLIFIER
MOTOR
LOAD
H
FIELDS OPPOSING
I
M
J
FIELDS ADDITIVE
K

Figure 7-22

SUMMARY

You use the left-hand rule for generator operation and the right-hand rule for motor operation.

Induced voltages and currents oppose the potentials which caused them.

Inertia and friction are the two primary physical characteristics that you must overcome to cause a mechanical object (armature) to rotate. Inertia and friction are both maximum when the motor is at rest.

Torque and motor speed are inversely proportional. The faster a motor turns, the less torque it develops. Motor speed is usually referred to as either synchronous or asynchronous speed. A synchronous motor's armature turns at almost the same speed as the field windings. An asynchronous motor's armature lags the field windings by an angle of up to 90°. This lag angle is called slippage. When an armature lags the field by 90°, maximum torque is developed.

One cycle of armature rotation is equal to 360°. One cycle is also equal to 2π radians. One radian is equal to approximately 57.3°. Two π is usually rounded off to 6.28. A radian is an arc equal to the radius of a circle.

DC motors are more versatile than AC motors.

Motors are usually classified by their construction. They can be series, shunt, or compound motors. A series motor has the field and armature in series with each other. The shunt motor has the field and armature windings connected in parallel. In a compound motor, one winding is in series and the other winding is in parallel.

The series motor is the most common type of motor. You can use it with AC or DC voltages, and is sometimes referred to as a universal motor. When you use a series motor, you must use a resistive load to prevent motor runaway, if the load opens. When they are used in an AC application, you should add resistance in series with the brushes to reduce arcing. Arcing can destroy the motor's armature, as well as the brush face.

The main cause of a malfunction in DC motors is usually brush related.

AC motors are usually referred to as either single-phase or three-phase motors. Most fractional horsepower motors are single-phase. Most motors rated at more than one horsepower are polyphase motors. The term polyphase means more than one phase.

Most two-phase motors are used as synchro or servo motors. The three-phase motor is considered to be the most popular type of polyphase motor for industrial applications.

In a single-phase motor, the start field winding is usually placed at 90°, in reference to the armature. This provides a maximum induced current to cause initial rotation. When you add resistance in series with the field winding, you reduce the current and decrease the induced (opposite polarity) voltage. This decrease in opposing potential causes the motor to increase RPM. When you add the resistance in series with the armature, the drive current decreases and the motor slows down. Motor speed is directly proportional to drive current, and inversely proportional to magnetic field strength.

In a two-phase motor the fields are 180° out-of-phase. The motor is controlled by 2 separate inputs. When you want to reverse its operation, you reverse its inputs. This type motor is normally a nulling device.

The three-phase motor has the fields separated by 120° and may use either the delta or Y (star) wiring configuration.

Field windings in a motor are called stator windings. The rotating conductor is called the armature or rotor.

An AC motor's speed (RPM) is directly proportional to applied voltage and frequency and inversely proportional to the number of poles. In a simple, three-phase motor, each field has 2 poles.

Motor regulation is expressed as a percentage. The formula for % of regulation is:

$$\frac{\text{no load speed} - \text{full load speed}}{\text{full load speed}} \times 100$$

The simplest motor control device is a series resistor. Anytime you add resistance in series, motor speed decreases. You can use a potentiometer to control a DC motor's speed and direction of rotation.

Other motor controls are relays, limit switches, thermo-switches, centrifugal switches, on/off switches, and radio-frequency-controlled devices.

The synchro and servo systems are examples of motor control mechanisms. The main difference between a synchro and a servo system is that the synchro has unity gain and the servo has a very high gain.

The synchro system is made up of a synchro transmitter (TX), differential transmitter (CDX) or receiver (CDR), and a synchro receiver (RX).

The servo system is a synchro system with an amplifier added.

You can operate both synchros and servos with either closed or open loops. With a closed-loop system, a sample of the output is fed back to the input.

In both synchro and servo systems, the transmitters are not free to turn. The receivers in both systems are free to turn. The synchro system is usually used to drive a pointer or dial indicator. A servo system is used to control a heavier load.

UNIT EXAMINATION

The following multiple choice examination is designed to test your understanding of the material that was presented in this unit. Place a check beside the multiple choice answer (A, B, C, or D) that you feel is most correct. After you complete the examination, compare your answers with the correct ones that appear after the exam.

1. The most common type of fractional horsepower motor is the:

   A. series type.
   B. shunt type.
   C. compound type.
   D. 3-phase induction motor.

2. The most common type of multiple horsepower motor is the:

   A. series type.
   B. shunt type.
   C. universal type.
   D. 3-phase induction motor.

3. The primary advantage of the shunt-wound motor is its:

   A. simple construction.
   B. almost constant speed characteristic.
   C. flexibility.
   D. high-torque capability.

4. The most serious disadvantage of the DC series motor is its:

   A. tendency toward thermal runaway.
   B. low-torque capability.
   C. constant-speed characteristic.
   D. complexity of construction.

5. The universal motor is a modified:

   A. shunt type.
   B. compound type.
   C. series type.
   D. induction motor.

6. To develop maximum torque:

   A. the start winding is in series with the armature.
   B. the run winding is in series with the armature.
   C. the start winding is offset from the armature by 90°.
   D. the run winding is offset from the armature by 90°.

7. You add a capacitor to a motor's circuit to:

   A. increase operating speed.
   B. increase starting torque.
   C. cause the motor to operate at a constant speed.
   D. increase a motor's horsepower rating.

8. When you increase a motor's field strength it:

   A. increases its speed.
   B. decreases its torque.
   C. increases friction.
   D. decreases its speed.

9. An example of a 2-phase motor is the:

   A. synchro motor.
   B. multiple horsepower motor.
   C. compound motor.
   D. polyphase motor.

10. In a 3-phase motor the field windings are:

   A. separated by 90°.
   B. separated by 180°.
   C. physically separated by 120°.
   D. electrically separated by 120°.

11. A motor develops maximum torque:

   A. when it operates at its synchronous speed.
   B. when it operates at its asynchronous speed.
   C. upon initial start.
   D. when it operates at its maximum speed.

12. To reverse the direction of rotation of a 3-phase motor, you can:

    A. reverse one of its inputs.
    B. reverse two of its inputs.
    C. reverse the AC power plug.
    D. reverse the field and armature windings.

13. A 3-phase motor is turning at its operating speed with a light load. If one winding opened, the motor would:

    A. continue to turn, but at a slower speed.
    B. increase speed.
    C. stop turning.
    D. rapidly overheat.

14. Select the correct statement for a 3-phase motor.

    A. Delta wound and star wound mean the same thing.
    B. Changing from delta wound to Y wound increases current.
    C. Changing from delta wound to Y wound increases voltage.
    D. Changing from Y wound to star wound increases torque.

15. Two pi radians are equal to:

    A. one alternation.
    B. 180°.
    C. 360°.
    D. the period of a sine wave.

16. A differential synchro is used in a servomechanism as the:

    A. prime mover.
    B. amplifying block.
    C. input device.
    D. error detection device.

17. In servo system the component that is usually free to turn is the:

    A. servo transmitter.
    B. servo receiver.
    C. synchro components.
    D. differential transmitter.

18. The characteristic that usually separates a servo system from a synchro system is:

    A. the ability to control at a distance.
    B. automatic correction.
    C. gain.
    D. the ability to detect errors.

19. Select the correct statement.

    A. The servo motor has 3 stator and 3 rotor windings.
    B. The rotor windings of a servo are separated by 120°.
    C. The synchro motor has 3 stator windings and 2 rotor windings.
    D. The turns ratio between a synchro's rotor and stator windings is 1:1.

20. When a 115 volts is applied to the rotor of a servo motor, the maximum voltage developed across any stator winding is approximately:

    A. 115 volts.
    B. 78 volts.
    C. 52 volts.
    D. 26 volts.

EXAMINATION ANSWERS

1. A — The most common type of fractional horsepower motor is the DC series, permanent magnetic type. It is the type used in inexpensive toys.

2. D — The most common type of multiple horsepower motor is the 3-phase induction motor. It is the type used in electric dryers, washing machines, and numerous industrial applications.

3. B — The shunt type motor is used in AC applications and has an almost constant speed characteristic.

4. A — The DC series motor should always have a series load to prevent thermal runaway.

5. C — The universal motor is so called because it can operate with either AC or DC voltages. However, it is more efficient when it is used with DC voltages.

6. C — Maximum torque is needed and created at the time of initial start. Maximum torque helps the motor overcome initial friction and inertia.

7. B — The addition of a capacitor to the motor's circuitry causes the phase difference to be approximately 90°. This increases starting torque for the motor.

8. D — Speed is inversely proportional to field strength.

9. A — Synchro and servo motors are the most common types of 2-phase motors that are used in homes and industry.

10. D — The stator windings in a 3-phase motor are electrically separated from each other by 120°.

11. C — The current demand is maximum upon initial start. At this time, there is no electromagnetic feedback to oppose rotation. Therefore, torque is maximum.

12. B — You can reverse two of the input windings on a 3-phase motor to reverse its direction of rotation.

13. A — Although a 3-phase motor with an open field winding may not start rotating, if it was already operating when the field winding opened, and it was under a light load, the speed of rotation will decrease. You may or may not be able to visually detect this decrease. The motor will also start to heat. For this reason, you should periodically check the speed of all 3-phase motors.

14. C — Changing from delta wound to Y wound increases the resistance and decreases the current. This results in a higher output voltage, but at reduced current.

15. C — One radian is equal to approximately 57.3 degrees.

$$6.28 \times 57.3 = 360 \text{ degrees.}$$

16. D — The differential synchro is used as the error detection device in a servomechanism system.

17. B — The only difference (electrically) between the servo or synchro receiver and transmitter is that the receiver is free to turn and the transmitter is not free to turn.

18. C — The servomechanism system contains a prime mover, error detection device, and amplification. The synchromechanism is usually a direct drive system with a 1:1 coupling ratio and no gain.

19. D — The turns ratio of a synchro (rotor to stator) is 1:1. The turns ratio of a servo motor is 2.21:1.

20. C — The maximum voltage induced across any stator winding in a 115 VAC servo motor is 52 volts. The turns ratio is 2.21:1.

$$115/2.21 = 52 \text{ V.}$$

UNIT 8

AC HOME APPLICATIONS

CONTENTS

INTRODUCTION

This unit is designed to provide you with a better understanding of AC electrical systems that you use in your home everyday. Many people take AC for granted. They turn on lights, cook meals, watch TV, stay warm, and hundreds of other applications daily, but don't think about how the various equipment are powered.

There are various RULES about what you can and can't do to house wiring. These rules fall into Electrical Codes and are controlled by government regulations. The government regulations come from the federal government, state government, county government, and even city and town codes. This course is only informational and not designed to supplement or supersede any regulations (codes) that apply in your district. In many areas, unlicensed persons (home owners) are allowed to do little more than change fuses, reset circuit breakers, and plug components into existing power outlets.

The purpose of electrical codes is to safeguard people and property from hazards that are associated with electricity. The exact codes vary from location to location. You should check with the local power company and the building inspector assigned to your district, before you make any changes to existing wiring. In many cases, electrical wiring changes must be done by a locally licensed electrician.

Earlier, this course described the power company and their high voltage power line. This unit picks up this description at the high voltage power line and continues to the individual service drop. You will then follow the routing of the service drop through a typical house.

Read the unit objectives carefully. They will help you identify and relate the various text material to common knowledge and electronic rules and principles you studied earlier.

UNIT OBJECTIVES

When you complete this unit you will be able to:

1. Explain the term service drop.

2. Identify the point at which the home owner's responsibility begins.

3. Explain the term power distribution box.

4. Calculate the maximum AC load for a given power outlet.

5. Explain the limitation that is placed on paralleling loads.

6. Name the two common types of safety devices which are used to disconnect excessive loads from their voltage source.

7. Identify which motors in your home are universal types and which are single-phase, two-phase, and three-phase motors.

8. Use the data that is supplied on a typical appliance's nameplate to calculate the current, voltage, and power that it requires to operate.

9. List the common electrical safety equipment that should be in every home.

10. Identify the type circuit that is used to recharge DC appliances such as cordless electric shavers, smoke detectors, portable mixers, and cordless hand held vacuum cleaners.

11. Identify potential electrical fire hazards in your home.

12. Recognize a blown fuse.

13. Explain the advantage and disadvantage of fuses when they are compared to circuit breakers.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "The Service Drop."	________
☐ Complete Programmed Review Frames 1-14.	________
☐ Read "Paralleling Loads."	________
☐ Complete Programmed Review Frames 15-21.	________
☐ Perform Experiment 12: Designing AC Loads.	________
☐ Complete Programmed Review Frames 22-32.	________
☐ Read "Safety."	________
☐ Complete Programmed Review frames 33-50.	________
☐ Study the Summary.	________
☐ Complete the Unit Examination.	________
☐ Check the Examination Answers.	________

THE SERVICE DROP

As a power company customer, you are primarily concerned with the power that actually enters your home. More specifically, you are concerned with the power that you must pay for. This is the power (I × E) you use from your service drop.

Earlier in this course, you learned that the power company transports power at extremely high AC voltages and low current values. They do this because it is easier, safer, and less expensive than transmitting low voltages at high currents.

However, before you can use the electrical power in your house, it must be converted to a lower voltage and a higher current. The service drop accomplishes this (see Figure 8-1).

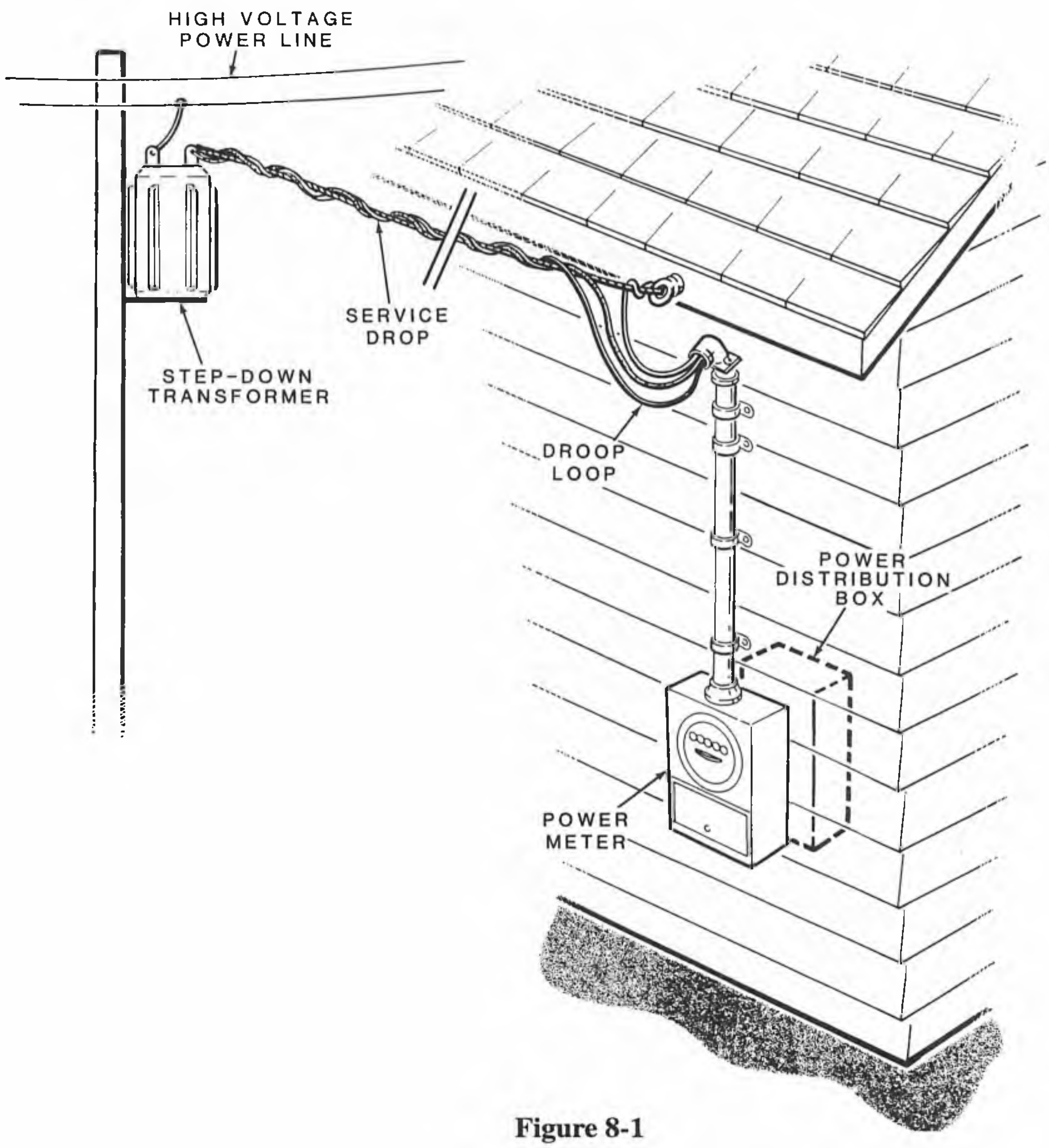

Figure 8-1
The service drop.

Transformer

The power company's main line is fed into a step-down transformer. The transformer lowers the line voltage from an extremely high voltage to the 120 volt, 60 hertz source that is supplied, through the service drop, to the individual customer or household.

The transformer, mounted either on a power pole or underground on the utility company's right-of-way, determines how much power its secondary can supply. The transformer is usually protected by circuit breakers that are mounted directly on the transformer or in a power company utility service box.

The transformer may supply power to more than one service drop or residence. Therefore, a power failure in your home may be caused by your neighbors. The power line in this example is called a common or shared feeder line. Even when you don't share a transformer with your neighbor, weather or some other disturbance in the line can cause your power loss.

Before the service drop enters your house, it passes through a droop loop. The droop loop prevents rain and moisture from draining into the wall where it could cause damage by rotting the wall or cause short circuits. The droop loop is designed to route water away from the house.

The service drop is usually 3 wires that provide 120 volts, 60 Hz service to the house. Two of the lines are 180° out of phase with each other. You can use the two lines that are out of phase by 180° to provide a 240 volt source. You cab also use each of the two lines as 120 volt sources. The service drop is routed through the electric company's power meter, and terminated in a power distribution box.

Power Meter

The power meter is usually mounted on the outside wall of the house, near the power distribution box. The service drop also has an ampere rating. This is the maximum current that can be supplied by the service drop. Normally, single family houses have either, a 100 ampere service (for older houses), or 200 ampere service (for newer and larger homes).

Service ampere rating is an important consideration when you buy a house. For example, some older houses are wired with a 60 ampere service drop. When the house was originally wired, it may have been heated with fireplaces or oil space heaters. However, there have been numerous electrical appliances marketed in recent years that were not available when the house was originally wired.

For example, suppose you buy an older home and install an electric furnace, refrigerator, freezer, garbage disposal, electric dishwasher, electric hot water heater, electric range, radio, TV, electric can opener, garage door opener, a well motor, and a variety of plug-in appliances. You may then find that the service drop is not equipped to handle the load. When this happens, you must contact the power company and arrange for an increase in your service drop and hire a licensed electrician to install another power distribution panel.

The electric power company's meter has a tamper proof seal that must not be removed. The power company reads the meter, usually monthly, to determine the power actually used by the residence. They then compute your electric bill. The power that you consume (use) is rated in kilowatt hours and it has a sliding rate scale. Once you surpass their standard fixed rate, the more power you use, the cheaper the rate per kilowatt hour.

The electric company reads the power meter that is attached to your house. They read the 5 dials at the top of the power meter from left to right. The left-most dial is the most significant digit. Note in Figure 8-2 that there is a small 1 located near the left dial. The 1 marks the most significant dial for the meter reader.

The meter in Figure 8-2 reads 25050, in kilowatt hours. Assume that the electric company charges .045 cents per kilowatt hour for the power used. Compare the meter's present reading (25050) to the reading on file from the last reading (for example 24050). You will see that at the start of the pay period (the last time the meter was read) to this meter reading there is a difference of 1000 kilowatt hours. This is the power that you actually used during the pay period. The cost of the power used is:

$$1{,}000 \times 0.045 = \$45.00.$$

The electric company's rate varies from one company to another. The rate also varies due to the amount of power that you use. To find the exact rate for your usage, you can contact your local power company, or you can divide the cost of the power by the amount of power used to calculate the rate. This information is included as part of your electric bill that comes from the power company.

Examine the power meter attached to your residence. The rotating dial in the center of the meter is actually keeping pace with the rate at which you are using power. The more power you use the faster the dial turns.

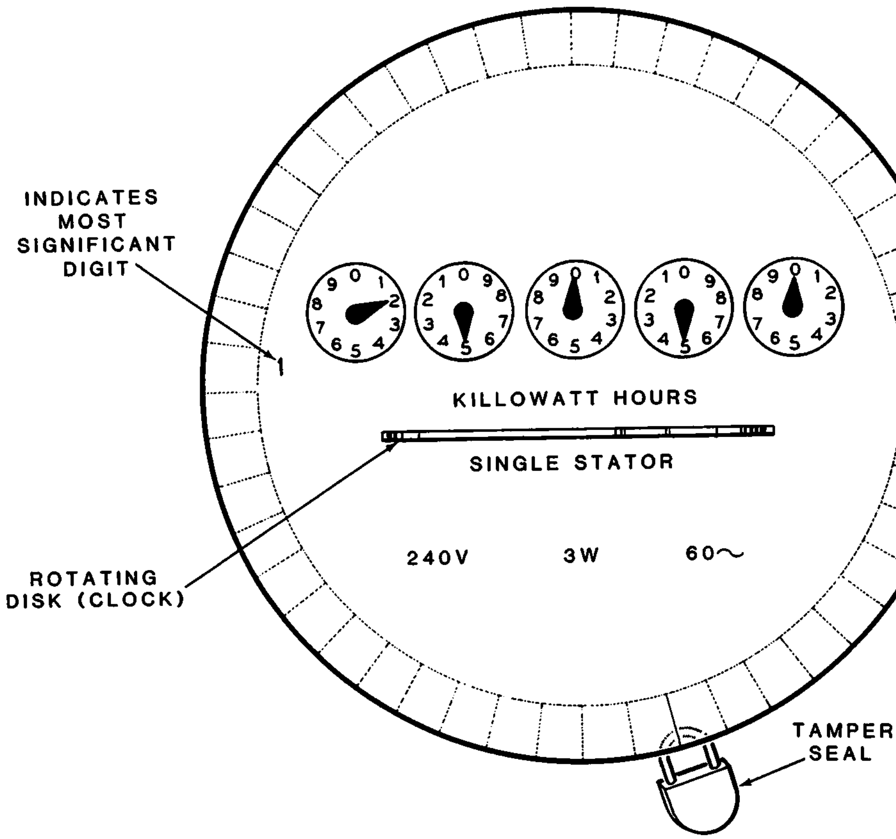

Figure 8-2
The power meter.

There may be additional charges on your electric bill such as cost recovery factor, which varies month to month and power company to power company. A tax is also added to your bill. Another charge that is common on electric bills is for rented equipment. One example of rented equipment is the security light that the power company installs and maintains at your request. A typical electric bill is shown in Figure 8-3.

SERVICE PERIOD FROM	TO	METER READINGS PREVIOUS	PRESENT	kWH USED
09-30	10-29	24050	25050	1000

	AMOUNT
BALANCE AS OF LAST BILLING DATE	50.00
PAYMENT RECEIVED 10-03	50.00
PREVIOUS BALANCE	00.00
1000 kwH USED THIS PERIOD	45.00
POWER SUPPLY COST RECOVER FACTOR AT .005/kWH	5.00
SECURITY LIGHT RENTAL	4.50
TAX AT 5%	2.70
TOTAL	57.20
DUE DATE 11-15	PAY THIS AMOUNT 57.20

Figure 8-3
Typical electric bill.

When you compare your electric bill month-to month you can ensure that the power company doesn't make a mistake on your electric bill. You will also know when your bill has been estimated and how much you have been overcharged or undercharged. This eliminates the surprise, when they actually read the meter and make the adjustment, to compensate for the estimated bill.

On the bottom of the electric bill, your cost per day is calculated for you. This is the average cost per day for that particular pay period. When these numbers change drastically, from one pay period to the next, there should be a valid reason. The reasons that are most common are, additional people using power (house guests), and severe changes in weather.

Power Distribution Box

The power distribution point of the power system is the dividing point between what you own, and what you rent from the power company. Even though the utility pole, transformer, and power meter may be on your property, they belong to, and are maintained by, the power company. Power companies as well as other public utilities have a right-of-way under, over, or through private property.

A power distribution box, like the one shown in Figure 8-4, separates the service drop into power busses. The number of busses in a distribution box may vary from house-to-house. A power buss is the voltage source or sources which are located inside the power distribution box.

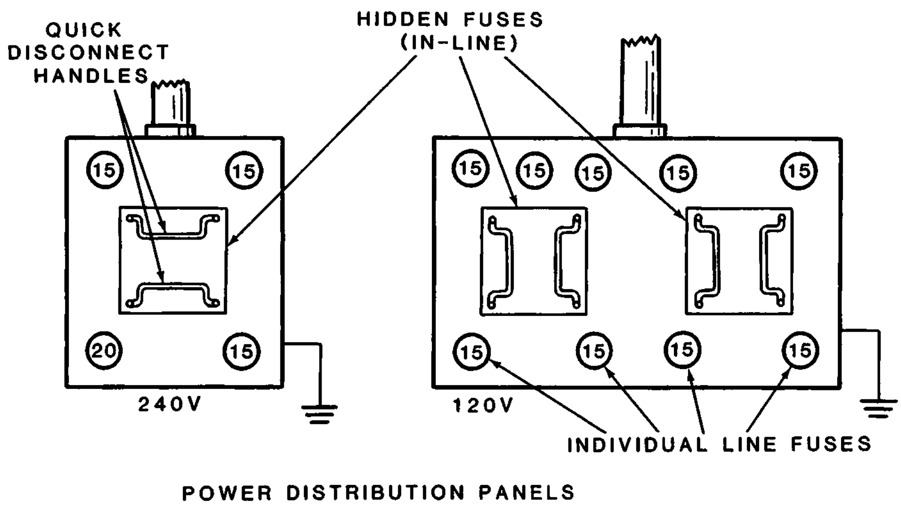

Figure 8-4
A 200-ampere distribution box.

Generally, the incoming power is divided into two busses. Each buss is protected by a series in-line fuse. In the case of a house with 200 ampere service, usually four 50 ampere fuses are used. These fuses are located inside a plastic housing, and are used to disable power to your house. The electrical code book states that you can use no more than six switches to disconnect complete power. That means that you could have your service drop divided into 6 separate buss boxes, if you can disable each buss box by a single switch.

Grounding The Power Box

The power distribution box must be earth grounded. One very effective earth ground is the cold water input pipe to your house. You also can drive a copper solid conductor into the ground to a depth of 4 feet to create another effective earth ground. A heavy conductive wire is then bolted between the grounding rod and the chassis (frame) of the power distribution box.

Do not use your hot water pipe for a ground because it may not provide a good ground. The heat from the pipe causes the wire to oxidize and corrode. This causes the ground to become ineffective after a period of time.

Wire Gauges

Another consideration when you wire a house is the gauge of wire that you must use. Figure 8-5 is a list of standard wire gauges and their current ratings.

WIRE GAUGE	CURRENT RATING
# 6	60A
# 8	40A
#10	30A
#12	20A
#14	15A

Figure 8-5
Copper sire gauge chart.

Most of the wiring inside houses is #12 gauge insulated copper wire. An electric range and clothes dryer may require a much heavier (lower number) gauge wire. The service drop into your home is a very large diameter wire. In many cases, you can see the size of the bare conductor that enters the power meter and the power distribution box from the service drop. If you compare these wires to the size of the wires that enter your home to supply power, to individual loads, you will notice the difference in size.

Programmed Review

1.	The service drop is connected to the main power line through a ________-________ ________.
2.	(step-down transformer) The service drop has a voltage and ________ rating.
3.	(current) The service drop is maintained by the power company and includes the ________, ________, and ________.
4.	(transformer, power meter, input power lines) The power distribution box is the responsibility of the ________ ________.
5.	(home owner) How many dials are on the standard power meter to record power used? ________.
6.	(five) The power company charges for power by the ________-________.
7.	(kilowatt-hour) What part of the power meter measures the rate at which power is used? ________ ________.
8.	(spinning dial) Which dial on the power meter designates the most-significant digit? The ________-________ dial.
9.	(left-most) The most common service drop for new houses is a ________-ampere service.
10.	(200) The voltage from the service drop is a/an ________ value.
11.	(120) The power distribution box divides the service drop into ________ ________.

12.	(load lines) The power distribution box is protected by ____________-____________ fuses.
13.	(in-line) What is the maximum number of disconnects which can separate house hold current from the service drop? ____________.
14.	(six)

PARALLELING LOADS

Inside the individual buss box, the circuits may be split into separate lines, and are fuse or circuit breaker protected against circuit overloads. These safety devices open the current path to disconnect shorted appliances or wiring from the source voltage. Fuses and circuit breakers protect the loads from the source voltage, and in turn, protect the loads from supply surges.

Current Paths

Each current path is limited to a specific current load. In many homes, individual lines are protected by 15, 20, and 30 ampere fuses or circuit breakers. However, 15-ampere fuses are the most commonly used. Even wall receptacles and on/off switches, in most houses, are safety tested and rated for 120 volts at 15 amperes. This means that a buss line could safely carry a load of 1800 watts (120 V × 15 A).

For your own information, examine the power distribution box in your home. Note the current ratings that are printed on the fuses (and/or circuit breakers). Also note if it uses all fuses, all circuit breakers, or a combination of fuses and circuit breakers. You should know where the distribution box is located in your own home. You should also make sure that you have a supply of spare fuses for each rating that is used in your particular distribution box.

In Figure 8-6, you can pull the quick disconnect fuse blocks to disconnect all of the power used in the house. Each of the fuse blocks could be divided and still remain within code. Remember, all power must be disconnected by no more than 6 disconnects. In many power boxes, some or all of the disconnects are in the form of knife switches.

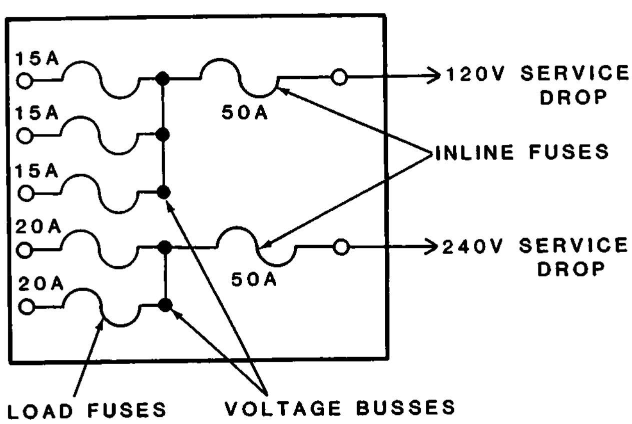

Figure 8-6
Power distribution box.

Each line from the distribution box is capable of supporting 15 A. The 15 A line is divided, by paralleling loads, until the parallel branch currents equal nearly 15 amperes. The wall plugs are usually paralleled in lighter loads, to allow additional loads to be plugged in.

Most overhead lighting is connected in parallel to each other, and then connected through a fuse to the 120 volt supply. In this case, the line could support thirty, 60 watt light bulbs.

$$P = 120\ V \times 15\ A \text{ or } 1800\ W$$

$$1 \text{ light bulb} = 60\ W$$

$$\frac{1800\ W}{60\ W} = 30$$

When you connect the lights in parallel, all of the lights won't go out when a single bulb fails. A light bulb usually fails because the filament (heating element) melts and opens.

One of the most common light bulbs in the average home are incandescent, 55 or 60 watt bulbs. The higher the wattage of the light bulb, the more light it puts out. The brighter the bulb, the more heat it dissipates. When you need more light in a specific area, a light fixture that contains more sockets is normally used.

You should use caution when you replace light bulbs with bulbs that have a higher wattage rating. Many lamps and light fixtures have warning statements that specify the maximum wattage rating that it can handle safely.

Home Appliances

Lighting and wall plugs actually account for very little of the total power used in homes. The majority of the power is used by large appliances. Cooking, heating, laundry, washing dishes, and taking baths consume well over half of all of the power that is used in a home. Figure 8-7 shows some typical household load currents with a 120 volt source.

For example, a single 1500 W, 120 V baseboard heater requires 12.5 A of current. If you had 4 of these heaters in a house, they would account for almost half of the 200 A service. When you use a 240 volt source to operate the same wattage heater, the current is less than 7 A.

A typical 14,000 BTU air conditioner that operates from a 120 volt source draws 8 A of current, while a 240 volt, 14,000 BTU air conditioner requires approximately 4 A of current.

ELECTRIC STOVE	30.0A
DISHWASHER	* 6.0A
1500 W HEATER	12.5A
ELECTRIC FURNACE	* 20A
HOT WATER HEATER	12A
CLOTHES DRYER	* 20A
GARBAGE DISPOSAL	* 3A
WASHING MACHINE	* 3.0A
FREEZER	*10.0A
REFRIGERATOR	* 3.0A
ICE MAKER	* 1.0A
ELECTRIC IRON	10.0A
ELECTRIC SKILLET	10.4A
TOASTER	8.0A
CAN OPENER	* 1.0A
LIGHTING 10% OF SERVICE DROP	20.0A
WALL PLUGS 10% OF SERVICE DROP	20.0A
TOTAL	189.9A

*INDICATES MOTOR CONTROLLED DEVICE

Figure 8-7
Typical household load currents.

Therefore, electric stoves, clothes dryers, air conditioners over 12,000 BTU, hot water heaters, and heaters rated over 1000 watts are usually are wired for 240 volts.

Appliances which are wired for 120 volts and 240 volts are not interchangeable. Special line cords and receptacles (see Figure 8-8) are required for 240 volt operation.

Since the power used is I^2R, this is much more efficient than the higher currents required by the 120 volt examples listed on this page.

Combining Loads

A power distribution box that contains 6 output lines can handle a maximum load of (6×1800 W) 10,800 watts or 180, 60 watt light bulbs. This is also referred to as 10.8 kW. Remember it is kilowatt (kW) hours that you pay for. For this to be true, all of the lights must be on for one hour. Even though your service may be rated at 200 amperes, rarely if ever, will you use maximum current on all of the lines at the same time.

Suppose that each output line, in each power buss, is capable of supplying exactly 15 amps. Also assume that the house is wired for 200 ampere service. In this case, the house could contain a maximum of 13 (200 divided by 15) separate and distinct 15 ampere lines, with 5 amps left over.

Fortunately, the peak or instantaneous power is not what you pay for, and you don't use all of your electrical appliances at the same time. The assumption of 13 balanced lines is also invalid. In every house, there are appliances that are wired directly into the power distribution box. Some of these are electric stoves, electric dryers, electrical hot water heaters, electric furnaces, and central air conditioners.

It is also safe to say that not all of your appliances are rated at 120 volts. Many of the larger load appliances are rated at 220/240 volts. This accounts for the variety in sizes of fuses and circuit breakers in the average home.

A 15 ampere branch can support 15 appliances that draw 1 ampere of current each. This can become a problem when you use extension cords. When you plug an extension cord into a wall outlet, you have no way of knowing how much of the branch current is already being used. That is why its not a good idea to connect extender junction boxes to wall plugs. When a branch becomes overloaded, in most cases it blows (causes to open) a fuse in the distribution power box. If the overload is severe enough, and the protective device fails to disconnect (open) the circuit, it could cause a fire.

Load Power

Power is dissipated in the form of heat. When you use light duty (small wire gauge) extension cords, they may overheat which softens their insulation. Also, when the insulation is hot, it tends to scrap off which causes a potential shock hazard or short circuit. Extension cords, as well as other power cords, tend to fray and become weakened at their ends. This is caused when you twist the ends as you plug and unplug them. This can also result in a short circuit and a potential shock hazard. You should take care not to route electrical wiring of any kind

where it could be exposed to pressure. Pressure can occur when step on the cord, drag objects over the cord, or even bend the cord around corners.

Never pull on the cord to unplug extension cords or appliances. Always grasp the body of the plug when you connect or disconnect a cord.

Inspect your extensions cords on a regular basis. Discard or repair any wiring that shows excessive signs of wear or cracked insulation.

A 2 horsepower (HP) circle saw, operated from a 120 volt source, draws 12.5 amperes of current.

$$1 \text{ HP} = 746 \text{ watts}$$

$$2 \text{ HP} = 1492 \text{ watts}$$

$$\frac{1492 \text{ W}}{120 \text{ V}} = 12.5 \text{ A}$$

Since most wall plugs are rated at 15 amperes, the circle saw in conjunction with only 3 other amps of load current, is an overload. When you use a light duty extension cord to power the circle saw, the extension cord will heat up. When you use insulated extension cords, periodically touch the cord to see if it is warm. If it is, lighten the load current or use a heavier (smaller number) gauge conductor.

Remember, the smaller the conductor's diameter the higher its resistance. Also, the longer the extension cord, the higher its resistance. For example, an extension cord has a resistance of only 2 ohms. When you connect it between the 2 HP circle saw in the earlier example and the 120 volt wall plug, the extension cord drops (12.5 A × 2 ohms) 25 volts. Thus, the saw has an applied voltage of only 95 volts. The lowered voltage causes the saw to turn at a lower RPM. You may not notice that it is not turning slower, but you will notice that it doesn't cut as efficiently as it should. This could lead you to the false assumption that the saw blade is dull and needs to be replaced.

Extension cords should be kept as short as possible. Power dissipated is I^2R, and a larger diameter shorter extension cord is less expensive and more efficient. The cord in the example (wastes) dissipates:

$$I^2R = (12.5 \text{ A})^2 \text{ (2 ohms)} = 312.5 \text{ watts.}$$

Broken strands within the conductor weakens an extension cord and increases its resistance by decreasing its diameter.

DIRECT WIRED APPLIANCES

Some appliances must be connected to specific receptacles. For example, the electric range and the electric clothes dryer are both 240 volt appliances but they have very different power requirements. The receptacles and power plugs for each of these appliances are matched so that they cannot be interchanged. When you have a wall plug wired for 240 volts, the receptacle is different than the standard 120 volt receptacle (see Figure 8-8). If you don't have a 240 volt wall receptacle in your home, the next time you are in an appliance store, examine the power plug on the heavy duty appliances. Note the difference between 120 and 240 volt appliance's line cords. This is another code restriction that you must adhered to.

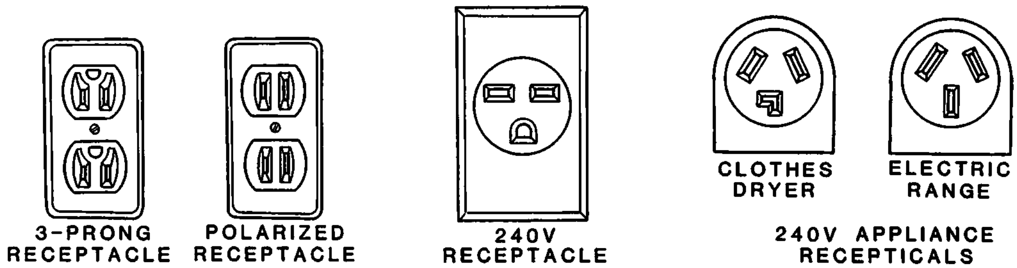

Figure 8-8
Typical home power receptacles.

You can wire other appliances that are never used at the same time in parallel into a single switch. For example, a dishwasher and garbage disposal should never be used at the same time. They can be wired to a single throw, double pole switch as shown in Figure 8-9. In this case, you can select either of the appliances, but not both at the same time. This wiring configuration allows you to combine loads that actually total more than the line can handle. However, since you can't operate them at the same time, it does not constitute an overload, and it will not blow the fuse in the distribution box.

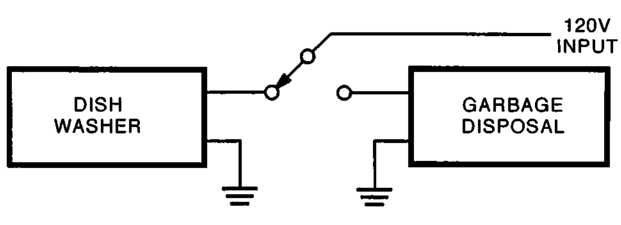

Figure 8-9
Either/OR circuit.

This is sometimes called an either/or circuit. You can select one or the other, but not both. Later, in your study of Digital Techniques, you will see that this is a commonly used circuit. This selective circuit is called an Exclusive OR in digital logic terms.

Another example of an either/or circuit, is a light that can be turned on or off from two different locations. For example, a switch at both exits of a room, or the light at the top of a flight of stairs. Figure 8-10 is a very simple wiring diagram that provides either/or control at two remote locations.

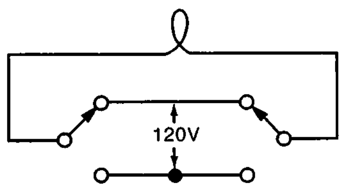

Figure 8-10
Two-location light switch.

TYPICAL HOUSEHOLD LOADS

Motors that have higher horsepower ratings are probably three-phase induction motors. Some of the small appliances and hand tools which are motor driven use series-constructed universal motors. Some of the motors in hand-tools and appliances are DC motors. An AC to DC rectifier circuit converts the input voltage that is needed to run these motors. The rectifier circuit is located inside the appliance or tool.

A television set probably has the highest voltage potential of all of the loads in your home. The high voltages are isolated and insulated from the operator. The voltage inside a television reach levels of approximately 35,000 volts (35 kV). However, the current draw of a television is very low (on the order of mA). The television's high voltage does not figure into the load current for a house. A transformer step up action produces the high voltage. A television set uses many DC voltage values which are obtained by rectifying the multi-tapped transformer's secondary windings.

The television system's antenna and rotor control uses a servomotor. The servo motor is a 2-phase motor that detects and corrects a programmed error signal. The servomechanism corrects the offset error that you introduce when you move the rotor controller. The servomotor repositions the antenna to the new reference to correct for the error.

An average household uses all of the concepts that you learn in DC and AC Electronics. An average home also contains many semiconductor devices, electronic circuits, and digital devices.

Programmed Review

15.	The two common protection devices which are used in the power distribution box are ____________-____________ ____________ and ____________.
16.	(slow-blow fuses, circuit breakers) The most common rated fuse in a power distribution box is usually ____________ amperes.
17.	(15) A 200-ampere service drop can supply ____________ watts to a house?
18.	(24,000) A 200-ampere distribution box can support ____________ 15-ampere loads.
19.	(thirteen) A power distribution box is usually grounded to ____________ ____________.
20.	(earth ground) Power lines which leave a power distribution box and enter your home are in ____________. series/parallel
21.	(parallel)

EXPERIMENT 12

Designing AC Loads

OBJECTIVES: *To convert loads into their current draws.*

To combine similar loads into groups that draw slightly less than 15 amperes.

To calculate the service drop that is required to support specified loads.

Introduction

In this experiment, you will calculate and organize typical AC loads that you can find in nearly all homes. This experiment provides information necessary for you to visualize the procedures you should follow when you wire a house. You will combine a variety of loads, and then connect them to load lines. The load lines are routed individually to a power distribution box fuse.

You should first divide the loads into groups which require 240 volts and those which require 120 volts.

You will then connect the loaded lines into power distribution boxes. Next, you will calculate the service drop that is required to support the full loads.

Procedure

1. On a piece of paper, draw a block diagram of the following loads.

   Three 1500 watt, 240-volt baseboard heaters.

   A washing machine with a 120-volt supply that draws 4 amps.

   A 3 HP, 240-volt three phase motor.

   Two 2 HP, 120-volt motors.

   Four 1/2 HP single-phase motors.

   Three 3-way lamps which are rated at 50, 250, and 350 watts each.

Light bulbs:

One 300-watt bulb.

Two 250-watt bulbs.

Three 100-watt bulbs.

Fifteen 60-watt bulbs.

2. Label each block as to its current requirement.

Discussion

You should have first divided the loads into two groups. One group should contain all of the 240-volt loads. The other group should contain all of the 120-volt loads. You can then assign a block to each load.

Next, you should have converted all of the loads (blocks) to their respective current draws.

For example: 1 HP is equal to 746 watts. When the source voltage is 240 volts:

$$\frac{746\ \text{W}}{240\ \text{V}} = 3.103\ \text{A}$$

As an additional safety feature, you should always round the current high.

3. Now, combine the similar individual loads into groups of less than 15 amperes.

4. Route the combined loads to their respective, fused, supply voltages.

5. Connect service drops to the supply busses and calculate the service drops which are required to support the loads.

The term similar load, in this case, means voltage supply. Therefore, you should have divided the loads into 240-volt sources and 120-volt sources.

You should have arranged each load or group of loads into slightly less than 15 A loads. Each 15 A load line should have been routed to a fuse in the appropriate 240 V or 120 V distribution box.

The opposite ends of the fuses should have been connected to the properly rated voltage buss. All of the 240-volt fuses are referenced to the same point. All of the 120-volt fuses are referenced to the same voltage.

The voltage busses should have been separated from the service drop by in-line fuses and quick disconnect switches. An example is shown in Figure 8-11.

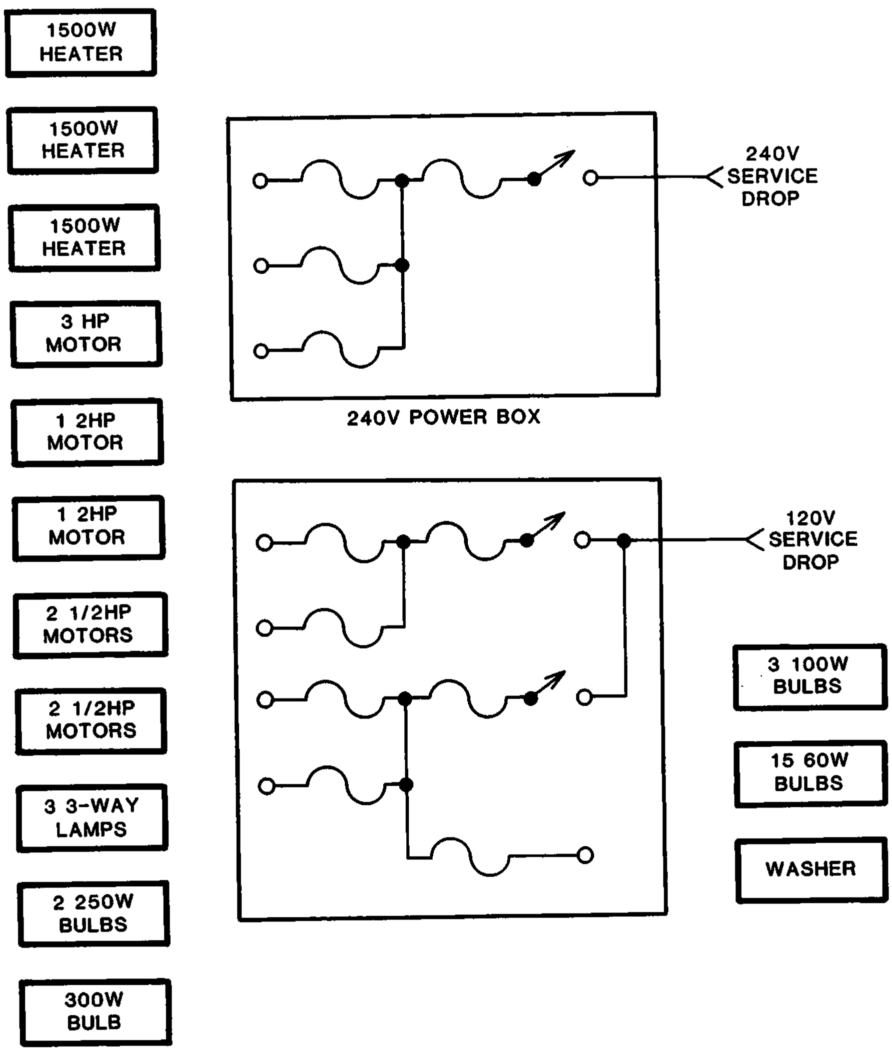

Figure 8-11

Summary

The 1500 watt, 240-volt heaters each draw approximately 6.3 amps.

The 3 HP, 240-volt motor, draws approximately 9.4 amps.

You can combine two of the heaters into a single load of approximately 12.6 amps. Therefore, the 240 power buss has three load lines.

A 2 HP, 120-volt motor draws approximately 12.5 amps. Therefore, each 2 HP motor should be wired individually to a load line.

A 1/2 HP, 120-volt motor draws approximately 3.2 amps. All four of the 1/2 HP motors could be combined into a load of approximately 12.5 amps.

You should use their maximum wattage ratings to calculate the current draw of the three 3-way lamps. The maximum rating of 1000 watts draws a current of approximately 7.5 amps. Two 250-watt light bulbs draw approximately 4.2 amps. A 300-watt light bulb draws approximately 2.5 amps. The combined current draw for this group is approximately 14.2 amps.

Three 100-watt bulbs draw approximately 2.5 amps. Fifteen 60-watt bulbs draw approximately 7.5 amps. The washing machine current is listed as 4 amps. This combined total is 14 amps.

The 120-volt buss has 5 load lines which go to 5 separate fuses in the 120-volt distribution box. The other end of all 5 fuses are tied together, and connected to the 120-volt buss.

The 120-volt buss should be wired through an in-line fuse and quick disconnect switch to the 120-volt service drop.

The 240-volt service drop must supply at least 34.6 amperes of current. This example used three 15-ampere load lines. Therefore, the 240-volt service drop should be capable of supplying 45 amps.

The 120-volt service drop must supply at least 67.5 amperes of current. The used five 15-ampere load lines. Therefore, the 120-volt service drop should be capable of supplying 75 amps.

All of the loads are rounded high. This provides additional protection for the fuses against surge currents.

There are other combinations that could have been used.

Note that the 120-volt load line on the right combines the washer with light bulbs. When the washer's motor first starts, and again when it changes speed, these lights may dim. This is the reason why appliances that draw large currents are not normally connected to the same line as lighting systems. There is also the possibility that surge currents may blow fuses.

Programmed Review

22.	The loads for a house power line are wired in ___________ .
23.	(parallel) The percentage of the service drop which is reserved for the lighting system in the average house is ___________ %.
24.	(10) Wall receptacles are usually paralleled with ___________ loads.
25.	(small) A 1500-watt baseboard heater is wired to a 120-volt source. The current draw for this heater is ___________ A.
26.	(12.5) The following light bulbs are connected to the same 120-volt service line. What is their combined current? ______________ . 15-watt bulb 40-watt bulb 55-watt bulb 60-watt bulb 75-watt bulb 100-watt bulb
27.	(1.81 amperes) A 1 horsepower appliance is connected to a 120-volt source. The current draw for this appliance is ___________ A.
28.	(6.22 A) Explain why some appliances are wired directly into the power distribution box instead of combined with other loads. ____ ____.

29. (These are usually very heavy loads, or they require special considerations for their power requirements.)

List four common power receptacles you can find in the average home.

1. ______________________.
2. ______________________.
3. ______________________.
4. ______________________.

30. (Your answers may include the following:

1. Standard 2-prong 15 A, 120-volt outlets.
2. Polarized 2-prong 15 A, 120-volt outlets.
3. Standard 3-prong 15 A, 120-volt outlets.
4. Standard 3-prong 15A, 240-volt outlets.
5. Electric range outlet.
6. Electric clothes dryer outlet.)

Why is it possible to parallel loads that exceed the fuse rating for their supply? ____
____.

31. (When you have loads that can't be used at the same time.)

List one household application that uses a single-phase, a two-phase, and a three-phase motor:

1. Single-phase motor. ______________________.
2. Two-phase motor. ______________________.
3. Three-phase motor. ______________________.

32. (1. Electric fan, 2. TV antenna control, 3. washing machine)

SAFETY

Most accidents happen in the home due to carelessness. Many of these accidents are a result of misusing electricity. Failure to think before you act causes many accidents. When you use an appliance for anything other than what it is designed for, it is an accident looking for a place to happen. For example, drying objects in the oven and lighting cigarettes with the stove's burner.

Safety Grounds

You may have noticed that some of your appliances have a round terminal on their power plug as shown in Figure 8-12. This ground terminal provides earth ground to the chassis of the appliance. When the chassis of an appliance has an earth ground, it helps prevent the appliance operator from receiving a shock due to an internal short in the appliance. The ground terminal is usually found on appliances that draw substantial currents, such as washing machines and power tools that are rated in horsepowers. For example, a 2 horsepower circle saw should have a 3-wire line cord and a 3-prong power plug.

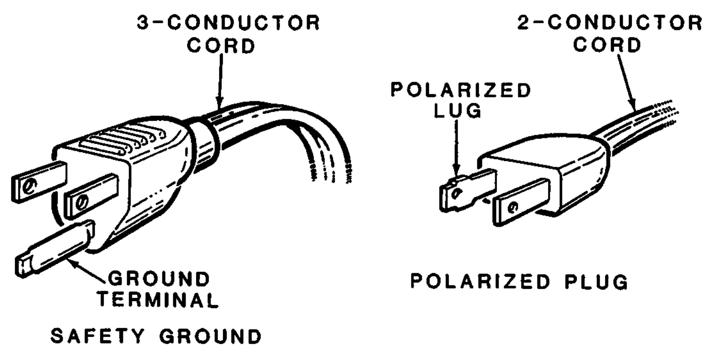

Figure 8-12
Grounded plugs.

Some 2-wire systems use polarized plugs. These line cords have one terminal that is larger than the other. This prevents you from inserting the line cord plug wrong (reversed by 180°). Many TV sets use polarized plugs. The larger terminal is connected internally to the TV chassis and acts as a safety ground. This type is often used in place of the 3-prong plug that is used on powered hand tools.

Never remove the ground terminal from any power plug. When a 3-input wall plug is not available, you can use a 3 to 2 terminal converter plug on a limited basis. These are not recommended, but they are available in many stores at a very reasonable price, and they are commonly used by individual home owners.

In residential wiring, ground leads are specified as either white or neutral gray in the electrical code book. This is important because inside electronic equipment a black wire is usually used as the ground (reference) wire.

Extension cords and line power cords cause many problems such as fires and burns. Improper use and improper maintenance are the usual cause of this problem. A shock hazard can result if you remove the earth grounding terminal or prong from a 3-prong plug. Fires may start if you overload wall receptacles. A shock hazard also exists if you use appliances when either you or the appliances are wet.

Improper fuses and fuses which have been bypasses can also start fires.

Improper cleaning causes fires. This is especially true of an electric cook stove. Excessive lint inside an electric clothes dryer can start a fire or cause a short circuit by collecting moisture when the dryer is not in use.

The heating element in a dishwasher, stove burner, and broiler rack gets extremely hot. They can cause a very serious burn even after they are turned off. You should never touch any element until it has had time to cool.

Electrical shorts and fires have been caused by bugs that shorted a voltage potential to ground. Fires have been started by rodents chewing insulated wiring. Red squirrels are prone to chew wiring when they get into the attic of a house.

Safety Devices

The most common safety devices in a house are the fuses and circuit breakers. They work even while you sleep. Smoke detectors also work while you sleep, but they don't prevent damage. Smoke detectors alert you so that you can prevent the damage from spreading. Automatic sprinkler systems are also automatic protection devices, although they are not normally used in moderate priced houses.

FIRE EXTINGUISHER

Other safety equipment that is not automatic or electrical include fire extinguishers. Every home should have a fire extinguisher that is in or near the kitchen.

Many fires in the home are caused by electrical shorts. Even when a fire is not started by electrical current, it is almost impossible to spray an area in a house without spraying an electrical component of some kind. Therefore, you should not use a water-filled fire extinguisher.

Instead, CO_2 type extinguishers are recommended for home fires. The carbon dioxide filler is very effective in fighting fires and it doesn't cause the mess that is associated with water-filled extinguishers. Also it doesn't cause shorts, the spray is easily controlled, and is much easier to clean up afterward. However, you should avoid breathing the carbon dioxide fumes for an extended period of time. Once the fire is out, ventilate the room so the fumes can rapidly dissipate.

To extinguish a fire, it must be deprived of either fuel or oxygen. Another way to put out a fire is to lower the temperature of the burning material below its flash point. There are common substances in virtually every kitchen that are effective on small fires. Salt and baking soda are excellent for extinguishing fires on electric stoves. Usually if the fire is confined to the inside of a pan, you can use a lid to shut off the oxygen supply.

FUSES

A fuse is a device which has almost zero resistance. It is designed with a center conductor that melts at a specific temperature. The resistance of the fuse and the current through the fuse generate the heat that is dissipated by the fuse. The fuse is in series with the household load. When the fuse's rating is has been exceeded, the fuse blows and causes that branch to become open. You can usually visually locate a blown fuse. You can see the discoloration or the open section of its element. Fuses in homes usually have glass bodies that screw into a fuseholder which is located in the power distribution panel. The fuse's rating is printed on the face of the fuse. Figure 8-13 shows typical household fuses. Figure 8-13A shows a good fuse while Figure 8-13B shows a blown fuse.

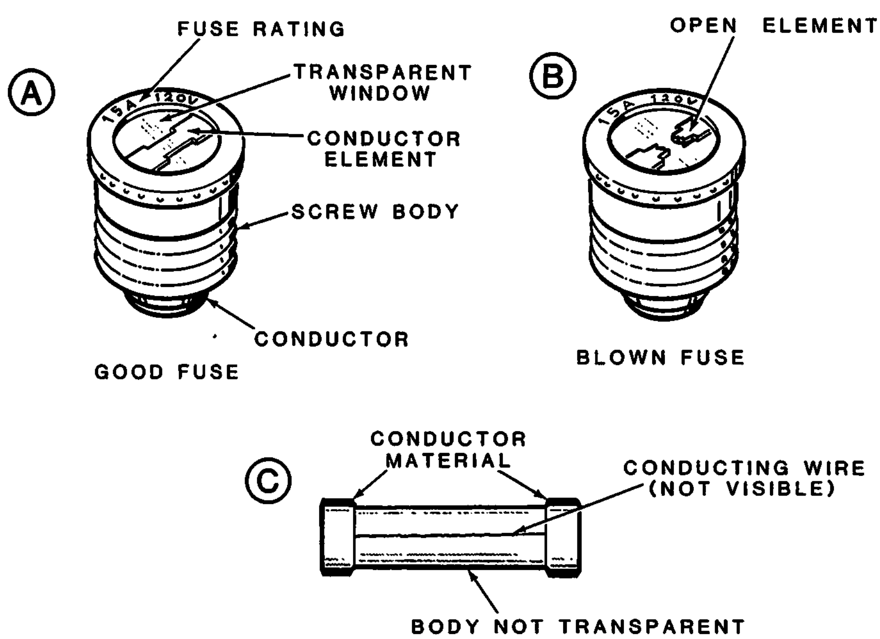

Figure 8-13
Typical household fuses.

The fuse shown in Figure 8-13C was referred to earlier as the hidden fuses that are mounted inside the quick disconnect plastic box. With this type fuse, you can't always determine if it is good or blown through a visual inspection. In this case, a meter is needed to verify the condition of the fuse. House fuses come in different physical sizes as well as current ratings. Every house should have a box of spares fuses.

Fuses can blow due to a line surge. Temporary arcing or shorting in the main power line or lightning can cause a line surge. Just because you blow a fuse doesn't necessarily mean that you have an overload in your home. When you replace the fuse and it blows again, you should assume that the problem (overload) is in your home. Unplug as many of the loads from that particular line as possible. Turn off loads that you can't unplug. Fuses which are used in homes are slow-blow type fuses. Slow-blow fuses have larger elements so they can withstand a current surge. If the current surge is within certain limits, and then decreases below the fuse's rating, the element will not get hot enough quick enough to melt. There are also fast-blow fuses, which blow the instant a current surge exceeds the fuse's rating.

Replace the fuse again. If the fuse doesn't blow, turn the loads on and then back off, one at a time. If you have a shorted load, the fuse will blow as soon as you plug in or turn on that load. Once you locate the faulty load, remove it (unplug it) and replace the fuse. Turn your other loads on to ensure that your wiring is good. If you can't isolate the problem to a load that is plugged in, you should call a licensed electrician, and turn the problem over to an expert.

CIRCUIT BREAKERS

Circuit breakers and fuses perform the same function. That function is to disconnect power.

The most common circuit breaker is actually a spring-loaded thermocouple. When the two metal contacts heat, they expand at different rates. When they exceed their operating temperature, the metal contacts separate. This separation opens the current path. Unlike the fuse, the circuit breaker is reusable. Once the metal contacts cool, you can reset the circuit breaker. (Some circuit breakers are magnetic devices. Magnetic circuit breakers are described in more detail in Electronic Circuits).

The reset characteristic makes the circuit breaker an ideal substitute for a fuse when you try to isolate the faulty load. There are also circuit breakers that are constructed to screw directly into the fuseholder, located in the power distribution box. The circuit breaker requires more time to react to an overload than an equally rated fuse. In most cases, the increase in time is insignificant, and is outweighed by the circuit breaker's ability to be reset (used more than once).

Circuit breakers which are most often used in homes look like a switch. They are labeled as to which position is off, and which position is on. Figure 8-14 shows a typical circuit breaker that is used in homes.

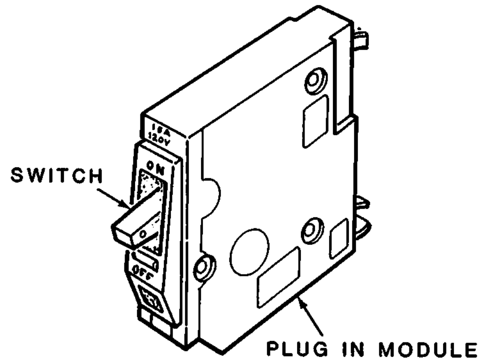

Figure 8-14
Plug-in, switch-type circuit breaker.

Figure 8-15 is a typical circuit breaker that can be used in a home to replace a fuse.

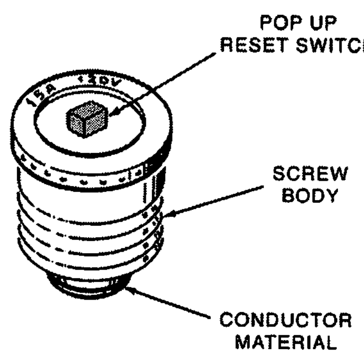

Figure 8-15
Screw-in circuit breaker.

Examine the back of your TV set (do not remove the back). There should be a red button sticking through the back. This is a circuit breaker (see Figure 8-16). This particular circuit breaker is designed to disconnect the television's high voltage circuits. When you enclose the TV in a small place, it can't dissipate enough heat. When the heat builds up, it may cause this circuit breaker to pop (open the circuit). When the circuit breaker pops, it shuts the TV off. In this case, there is nothing wrong with your TV. Once you allow the television set to cool, you can push the red button and hold it for approximately one second to reset the circuit breaker. Line surge can also cause the circuit breaker to pop.

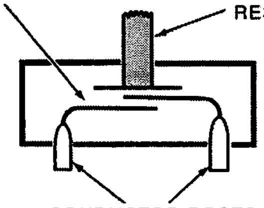

Figure 8-16
Typical TV circuit breaker.

Never hold the circuit breaker in longer than it takes for it to catch (set). If the circuit breaker pops again after the set cools, this is an indication of internal failure. Make no more attempts to reset the breaker.

Most garbage disposals are protected by a circuit breaker. The circuit breaker is mounted directly on the disposal's motor. Whenever the disposal is jammed by silverware or bones, the circuit breaker disconnects the circuit before the motor becomes damaged. In this case, turn the disposal off, free the obstruction, reset the circuit breaker, and turn the disposal on. If the circuit breaker pops again, your garbage disposal may be the problem.

Never hold a circuit breaker to prevent it from popping, as this could easily cause a fire. Even if it didn't start a fire, it might destroy your appliance.

Programmed Review

33. What is the main advantage of a fuse as compared to a circuit breaker? ____________________.

34. (speed of operation) Explain the term power buss. ____________________
____________________.

35. (A power buss is a point where several loads can be connected to the same potential.)

The circuit breaker operates on the same principle as a/an ____________________.

36. (thermocouple) The color of the wire that is specified by the electrical code for ground is ____________.

37. (white or neutral gray) The rounded center terminal on a 3-wire power plug is designed to be ____________ ____________.

38. (earth ground) Explain the term polarized power plug. ____________
____
____
____________________.

39. (A polarized power plug has one of its prongs larger than the other. It can only be plugged in one way. As example of this is a TV power cord. The large terminal is the ground terminal.)

Where are extension cords most likely to be damaged? ________
____________________.

40. (near the end) The most common cause of a blown fuse that services wall outlets is a/an ____________ circuit.

41. (overloaded) The greatest danger from an electric stove is a ____________.
shock/burn

42. (burn) The most important safety feature in a home is ____________.

43. (you) Automatic safety devices in all homes are ____________ and ____________ ____________.

44. (fuses, circuit breakers) An automatic safety device that you should install on every floor is a ____________ ____________.

45. (smoke detector) You should use a ____________ type fire extinguisher in a home.

46. (CO_2) You should always replace a blown fuse with a fuse which has ____________ ____________ ____________.

47. (the same rating) Fuses can be replaced with circuit breakers that have the same rating. ____________
true/false

48. (true) When a circuit breaker pops, can it be immediately reset? ____________
yes/no

49. (no) Why? ____________________________________.

50. (You must allow it to cool.)

SUMMARY

AC service drops are routed from the secondary of a step-down transformer as shown in Figure 8-17. The common voltages available to home owners are 120 volts and 240 volts. This voltage value is its RMS value and the frequency is 60 hertz.

Two of the 120-volt lines that are 180° out of phase can be used to provide 240-volt service. When the 240-volt service is available from wall plugs, the plugs must be specifically rated at 240 volts.

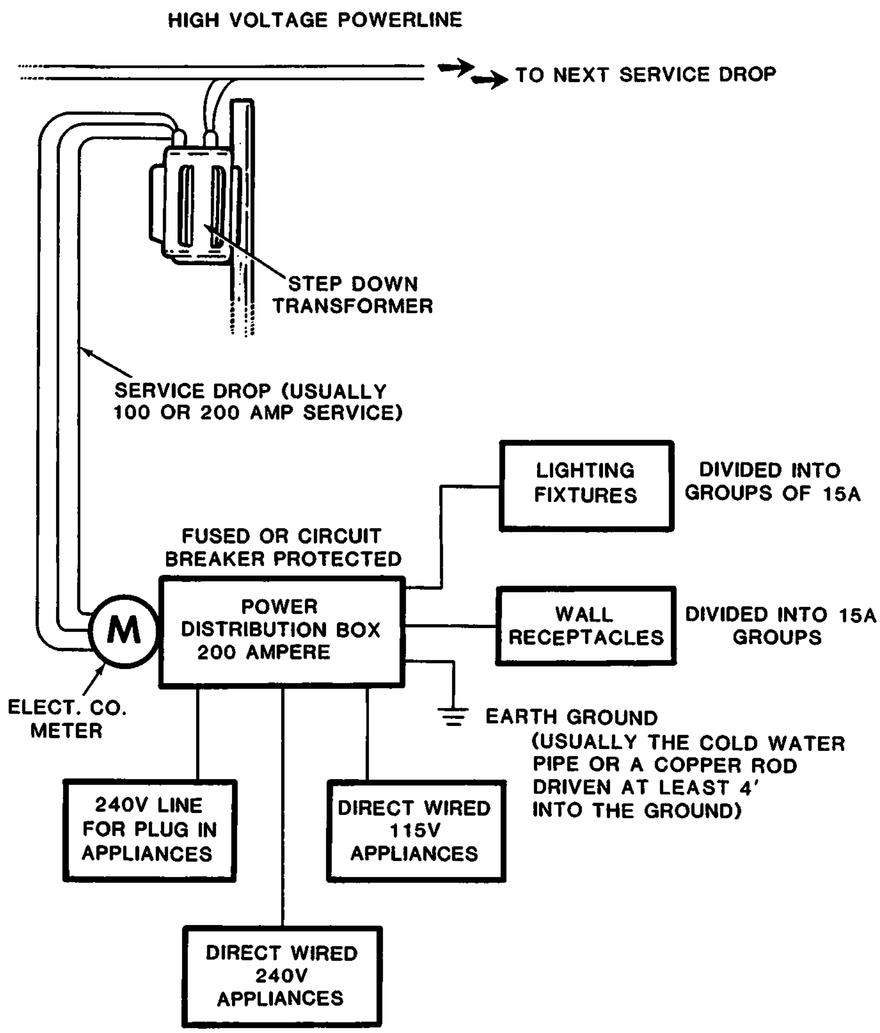

Figure 8-17
AC wiring block diagram for a typical home.

Two of the 120-volt lines that are 180° out of phase can be used to provide 240-volt service. When the 240-volt service is available from wall plugs, the plugs must be specifically rated at 240 volts.

Residential service drops are also rated in amperes. Houses usually have 60-, 100-, or 200-ampere service drops. With the advent of the wide variety of electrical appliances, the 200-ampere drop is the most popular. Even if you don't need 200 amperes, its nice to have the capability of adding loads, without having to first call the power company.

The power distribution box in your house must be earth ground referenced. This is usually accomplished by connecting the chassis of the distribution box to either a cold water pipe or to a copper rod that is driven 4 feet into the ground.

Another code requirement for a distribution box is that all household power must be routed through no more than 6 disconnects.

Household power is divided into busses and fused. The busses are then divided into power lines and fuses or circuit breakers protect these lines against overloads. The individual power lines are usually protected by 15-ampere fuses or circuit breakers. Load currents are paralleled until the branch currents total a little less than 15 amperes and the paralleled load is wired to the individual power line.

A 200-ampere service drop could be divided into 13 individual, 15-ampere power lines. The individual lines are then fused with the appropriate rated slow-blow fuse. The fuses are rated as slow-blows to prevent surge currents from blowing them. One type of surge current that could cause problems if slow-blow fuses are not used is when your washing machine shifts into the spin cycle.

The spin cycle starts a motor from stop under full-load conditions (tub full of wet clothes and water). This results in a high surge of starting current.

The largest household loads are used for cooking, drying dishes and clothes, heating the house, and heating water. These heavy loads are usually wired for 240-volt operation.

Approximately 10% of the total service drop is used for lighting. Another 10% is usually reserved for wall plug loads. These applications usually use 120-volt supplies. A single 15-ampere, 120-volt line is capable of supplying 1800 watts (15 A × 120 V). This could supply power to light thirty 60-watt light bulbs. The lights are paralleled in a house so that all of the lights don't go out when a single bulb opens.

Wall receptacles are usually paralleled with small loads. This ensures that the line will not become overloaded when you plug in appliances. 240 V and 120 V receptacles are constructed so that you can't plug appliances into lines that can't handle their load.

The most important safety device is the home owner. There is no substitute for common sense and attention to detail.

Commercial safety devices that are used in homes are fuses, circuit breakers, smoke detectors (one per floor), and a carbon dioxide (CO_2) fire extinguisher. Fuses and circuit breakers are considered to be protection devices for individual loads and the house itself. Smoke detectors are considered to be people protection devices. A handy fire extinguisher can prevent a minor fire from becoming a major fire.

A fuse operates (opens) faster than a mechanical circuit breaker. A fuse is a one-time device; once it blows, it must be discarded, and a new fuse of the same rating installed. When a circuit breaker pops (opens), you can reset it after it cools.

Besides the power distribution box, circuit breakers are commonly used in televisions and garbage disposals. Other appliances may also be fused or protected by internal fuses or circuit breakers.

UNIT EXAMINATION

The following multiple choice examination is designed to test your understanding of the material that was presented in this unit. Place a check beside the multiple choice answer (A, B, C, or D) that you feel is most correct. After you complete the examination, compare your answers with the correct ones that appear after the exam.

1. Select the statement below that best describes the service drop.

   A. The total power used by a household.
   B. The total power available to a household.
   C. The total current allowed per load line.
   D. The power listed on your monthly electric bill.

2. Power busses are located in:

   A. the power transformer.
   B. the electric power meter.
   C. the power distribution box.
   D. each load line.

3. The power to a household must be disconnected by:

   A. two or fewer than two switches.
   B. four or fewer than four switches.
   C. 6 switches or less.
   D. a single switch.

4. Individual load lines in most homes are protected by:

   A. two automatic disconnect devices in the distribution box.
   B. only the line fuse.
   C. only the in-line fuse.
   D. circuit breakers only.

5. In most homes, individual loads are connected:

   A. in series.
   B. in parallel.
   C. to individual load lines.
   D. in a series-parallel combination.

6. In household wiring, the color of the ground wire is:

   A. black or brown.
   B. red or green.
   C. green or white.
   D. white or gray.

7. Select the correct statement below.

   A. Circuit breakers operate faster than fuses.
   B. Quick blow fuses are used in most households.
   C. Circuit breakers are either electromagnetic or thermocouple devices.
   D. Each load line must be individually fused.

8. What percentage of the service drop is usually reserved for lighting in the average home?

   A. 10%
   B. 25%
   C. 50%
   D. 75%

9. The electric power that you are billed for is measured by the:

   A. watt.
   B. kilowatt.
   C. kilowatt hour.
   D. volt-amp.

10. A 3/4-horsepower motor operating with 120 V applied draws approximately:

    A. 4.65 amperes.
    B. 500 milliamperes.
    C. 90 amperes.
    D. 2.0 amperes.

11. A 300-watt light bulb, a 50-watt light bulb, and a 60-watt light bulb are paralleled. Their combined load is approximately:

    A. 3.5 7 amperes .
    B. 120 volts.
    C. 50 watts.
    D. 7 amperes.

12. Select the correct statement about wire size.

    A. The smaller the gauge the larger the diameter.
    B. The smaller the gauge the smaller the diameter.
    C. Wire gauge has to do with current capability not physical diameter.
    D. A wire's resistance is directly proportional to its diameter.

13. The most common household ground is the:

    A. hot water pipe.
    B. power distribution box.
    C. cold water pipe.
    D. steel rod driven into the ground.

14. The three most common safety devices in the average home are.

    A. fuses, circuit breakers, and fire extinguishers.
    B. fuses, circuit breakers, and smoke detectors.
    C. smoke detectors, sprinkler systems, and fire extinguishers.
    D. salt, baking soda, and fuses.

15. When you operate a 2 H.P. saw and a 1/2 H.P. drill at the same time from the same 120-volt receptacle:

    A. both appliances will function properly.
    B. the fuse will blow.
    C. both will function, but at reduced efficiency.
    D. the drill will function properly, but the saw will decrease speed.

16. The center rounded prong on a 3-prong plug should be connected to:

    A. chassis ground.
    B. the polarized terminal of the power plug.
    C. earth ground.
    D. the power distribution box.

17. Circuit breakers are preferred over fuses because they:

    A. are safer.
    B. are less likely to malfunction.
    C. last longer.
    D. can be reset.

18. If a 240-volt baseboard heater draws 5 amperes of current, its power rating is:

    A. 6000 watts.
    B. 1 kW.
    C. 1.6 H.P.
    D. 1 kW hour.

19. Which of the following home appliances is most likely to be wired for 240-volt operation?

    A. Garbage disposal
    B. Dishwasher
    C. Refrigerator
    D. Range

20. Excluding heating, where is most of the power that is used in the average home?

    A. living room
    B. kitchen
    C. dining room
    D. bath room

EXAMINATION ANSWERS

1. B — The service drop is usually defined as the maximum current available to a household.

2. C — The power busses are located in the power distribution box and they are protected by in-line fuses.

3. C — The electrical code states that you must be able to disconnect power to a household by no more than 6 switches.

4. A — Most of the load lines inside your home have two automatic disconnect devices. They are usually the in-line buss protector (fuse or circuit breaker) and the load line fuse or circuit breaker. In addition, many appliances have internal fuses or circuit breakers.

5. B — The loads that are combined to equal 15 amperes are connected in parallel. Also, the individual load lines are routed in parallel, from the power distribution box.

6. D — In residential wiring, according to the electrical code book, ground wires must be either white or neutral gray.

7. C — Slow-blow fuses are used in most homes, however, they still operate faster than circuit breakers. The circuit breaker is a thermocouple or electromagnetic device that requires time, to heat or establish a strong magnetic field, before it can disconnect.

8. A — The general rule for a residential lighting system is to reserve 10% of the service drop for lighting purposes.

9. C — The power that you pay for is measured in kilowatt hours. To calculate the amount of power that you used, subtract the power reading recorded on your last bill, from the meter's present reading.

10. A — One horsepower is equal to 746 watts. Therefore, 3/4 horsepower is approximately 560 watts.

$$560\ \text{W}/120\ \text{V} = 4.67\ \text{A}.$$

11. A — The combined load is 410 watts. The standard voltage for light systems is 120 volts. Therefore:

$$410\ \text{W}/120\ \text{V} = 3.42\ \text{A}.$$

12. A — The smaller the wire gauge, the larger the diameter of the wire. The larger the wire diameter, the higher its current handling capability. A 20-gauge wire has a larger diameter than a 22-gauge wire.

13. C — A cold water pipe is the best choice for ground in a home. The hot water pipe is also grounded, but the constant heating and cooling may cause the ground to become faulty after a period of time.

14. B — The three most common safety devices in the home are fuses, circuit breakers, and smoke detectors. They all work automatically to sense a danger.

15. B — When both appliances are used at the same time, they demand more current than the 15-ampere line is able to supply. Current is a demand quantity, and if the load demands, the source will supply up to the point where the safety device causes an open circuit.

16. C — The center rounded terminal on a power plug connects the appliance's chassis (metal frame) to earth ground. It is usually used for heavy current draw appliances and is a definite safety feature. It can reduce shock hazards. You should never bypass the safety (chassis) ground.

17. D — The primary advantage a circuit breaker has over a fuse is that you can reset it. A fuse must be discarded and replaced by a known good fuse with the same rating. Circuit breakers are very helpful when you troubleshoot a problem. Replacement fuses cost money when you guess wrong.

18. C — The power rating is:

$$I \times E \text{ or } 1200 \text{ watts.}$$

Twelve hundred watts is equal to approximately 1.6 H.P.

19. D — An electric range has the heaviest current draw and is, therefore, the most likely of the appliances listed to be wired for 240-volt operation. The other appliances listed are usually wired for 120-volt operation.

20. B — Most of the electric power in a home is used in the kitchen. The electric range, refrigerator, dishwasher, and garbage disposal are all heavy current draws. In contrast, most television sets draw currents in the mA range.

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